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CROP RESPONSES TO LIMING ON ACID SOILS OF ALBERTA
AND NORTHEASTERN BRITISH COLUMBIA

by



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A THESIS

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THE UNIVERSITY OF ALBERTA
FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Crop Responses to Liming on Acid Soils of Alberta and Northeastern British Columbia" submitted by Douglas Charles Penney in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

The main objectives were to determine the extent to which yields of various farm crops are limited by soil acidity in Alberta and northeastern British Columbia; and to find suitable soil tests to predict the effect of soil acidity on yields of different crops. There were three phases to the work. Initially a greenhouse experiment was conducted to determine the relative tolerance to acidity of some different species and varieties of crops. Subsequently several of those crops were grown in field experiments with and without lime on 28 typical acid soils. Finally, various soil tests were compared to crop response in the field experiments.

In the greenhouse pot culture experiment, the addition of lime to a soil of pH 5.0 and containing 8 ppm of 0.02M CaCl_2 -soluble Al increased the yields of barley, rape and alfalfa. The addition of 100 ppm of Mn to the soil produced Mn toxicity symptoms on alfalfa and rape but did not significantly reduce yields. Crop tolerance to acidity was in the order: oats > rape = barley >> alfalfa. Small differences in acidity tolerance were found among varieties of barley and rape but no differences were evident among alfalfa varieties.

Experiments were conducted at 28 field sites on soils ranging in pH from 3.4 to 6.1, and barley, rape, alfalfa and red clover were grown with and without lime at each of the sites. Soils at the 28 sites ranged widely in type, chemical characteristics and geographical location. Acidity tolerance, of the crops and varieties grown, was in the order: red clover > rape = Olli barley > Galt barley >

alfalfa. Nodulation of alfalfa was reduced by soil acidity when soil pH was less than 5.6 whereas, nodulation of red clover was reduced only when pH was less than 5.0. Response to lime obtained on the crops grown shows that soil acidity is a significant factor in crop production in the region studied, with alfalfa being the crop most affected.

Several soil criteria were used in correlation and regression analyses to assess their ability to predict crop response to lime. For barley and red clover, 0.02 M CaCl_2 -soluble Al gave the best prediction of response to lime. For rape, 0.02M CaCl_2 -soluble Al and Mn gave a better prediction of lime response than soluble Al alone. Soil pH was the most useful criteria for predicting response of alfalfa to lime.

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INTRODUCTION

Soil acidity as a factor in crop production has received little attention in the Canadian Prairie Provinces. Although Luvisolic soils, and the surface horizons of Solonetzic soils, are often moderately to strongly acid on the basis of pH, other characteristics such as high base saturation, neutral to alkaline subsoils and free lime occurring within the rooting zone have been cited as reasons why acid soil infertility is not inherent in such soils. In contrast to other regions where acid soils occur, lime has not been used or recommended for crop production.

The need for an investigation of the effects of soil acidity on crop production in Alberta was clearly shown by the results of recent experiments in the Peace River region; and by summaries of pH values of soil samples throughout Alberta as compiled by the Alberta Soil and Feed Testing Laboratory (ASFTL). Summaries by the ASFTL of some 81,000 farm samples show that 20.6% are $\text{pH} \leq 6.0$ and 3.9% are $\text{pH} \leq 5.5$. A summary map of average pH per township outlines the general distribution of acid soils in the province (Figure 1). Results of experiments conducted by the Soils Section, Research Station, Beaverlodge show marked increases in crop yields from application of lime to acid soils of the Peace River region. Hoyt and Nyborg at Beaverlodge have compared and developed analytical methods for predicting crop damage from acidity. Results of these investigations provide the framework for this study.

The infertility of acid soils has been attributed to many factors and the effects of soil acidity on crops varies widely among species and varieties. This study considers several factors of soil

acidity on a number of crops over a large geographic region. Therefore, it is evident that many aspects of soil acidity in this region will need further investigation. The objectives of this study can be summarized as follows:

1. To provide some estimate of the extent and degree of acid soil infertility in Alberta.
2. To determine the relative tolerance to acidity of some crop species and varieties over a wide range of soil and climatic conditions.
3. To compare various soil analyses as a means of predicting damage from acidity.
4. To provide a basis for recommending liming or use of acidity-tolerant crops on acid soils.

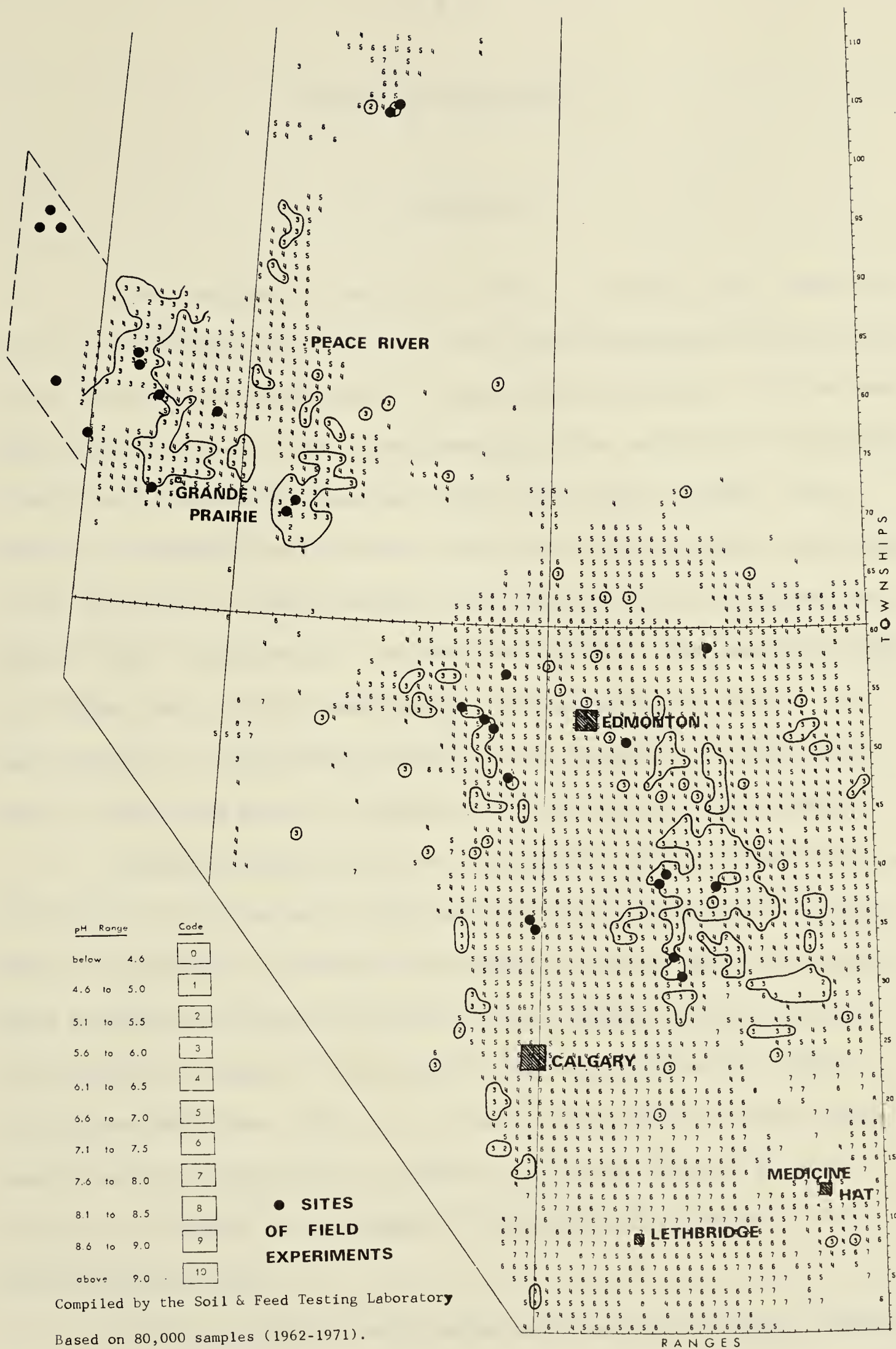


Figure 1. Distribution of acid soils and site locations of field experiments.

REVIEW OF LITERATURE

A. Introduction

The benefits of liming acid soils to increase crop production have been recorded since 200 B.C., and liming experiments have been conducted since the earliest years of agricultural research. Yet the most significant progress in our understanding of the many factors attributed to acid soil infertility have been made in the past 20 years. The extent and diversity of literature published on this subject, particularly in the past 10 to 15 years, makes a thorough review of the subject an arduous task. Consequently, the American Society of Agronomy published the review, "Soil Acidity and Liming", monograph No. 12, 1967. The publication is a comprehensive survey of the literature to 1966, and served as the main guide in assembling the literature in the thesis.

Factors commonly cited as causing infertility of acid soils are, deficiencies of Ca, Mg and P and toxicities of Al, Mn and Fe (Jackson, 1967). The effects of acidity on microbial activity and the release of plant nutrients from mineralization of soil organic matter are also investigated as causes of acid soil infertility (Hallsworth, 1958; Bartholomew and Clark, 1965). The economic importance of many legume species and the sensitivity of symbiotic nitrogen fixation to soil acidity is reflected in the number of investigations devoted to its study (Jackson, 1967).

Modern concepts of acid soils and their ion exchange chemistry developed during the 1950's and 1960's. As outlined by Coleman and Thomas (1967); Veitch (1902), Paver and Marshall (1934) and Schofield (1949)

showed that salt-exchangeable aluminum occurred in acid soils, but acid soils and clays were generally regarded as hydrogen and basic cation systems. Results of many investigations during the 1950's and 1960's established the importance of aluminum in the ion exchange chemistry of acid soils.

Studies of the physiological effects of soil acidity have been very diverse. Attempts to delineate specific causes of poor growth of plants on acid soils have often been of limited success (Jackson, 1967). Liming acid soils causes many characteristics to be changed simultaneously. This, coupled with wide variation among species and varieties in their tolerance to various components of acidity, has lead to many seemingly conflicting results. In recent years, progress in our understanding of acid soil chemistry and improved techniques for identifying physiological effects (particularly isotope tracer techniques) is resulting in rapid progress. At present, considerable attention is afforded to aluminum and manganese measurements in soils and plant material as criteria for assessing crop damage from acidity. Lack of specific symptoms of aluminum toxicity in many species can cause it to be overlooked in the presence of such things as Mn toxicity which is visibly evident but may cause little or no reduction in yield (Vlams and Williams, 1962).

B. Factors in Soil Acidity Damage to Plants

Of the many factors attributed to infertility of acid soils, the most commonly discussed are H-ion concentration, calcium, phosphorus and molybdenum deficiency, and aluminum, manganese and iron toxicity.

In addition many processes involved in plant nutrition, such as the mineralization and immobilization of N, P and S, development of mycorrhizal associations, and symbiotic and nonsymbiotic N fixation all may be affected by soil acidity (Jackson, 1967). The more pertinent of these many factors are reviewed here under separate headings.

1. Hydrogen Ion Concentration

The most widely used criteria for determining acidity of soils is pH. It is regarded as an empirical measurement in that uncertainty due to the suspension effect prevents precise definition of soil pH in terms of H-ion activity. The suspension effect is considered the most uncertain aspect of pH measurement and the mechanisms causing it are still a matter of debate (Coleman and Thomas, 1967). Two methods are commonly used to reduce uncertainty due to the suspension effect as influenced by electrolyte concentration. Schofield and Taylor (1955) proposed that pH be measured in 0.01M CaCl_2 and that the result be expressed as $\text{pH}-\frac{1}{2}\text{pCa}$ (lime potential). The second method involves the use of a concentrated salt solution such as 1N KCl. Coleman and Thomas (1967) indicate that the pH obtained with this concentrated salt solution indicates something about the exchange acidity of soils. For prediction of crop damage from soil acidity, the various methods of pH measurement have seldom been compared.

If aluminum and manganese levels are not toxic, H-ion concentration has little effect on growth of most plants until pH falls below 4.0 - 4.5 (Jackson, 1967). Since pH in this range seldom occurs under field condition, direct H-ion toxicity is of minor importance except when legume crops are grown and symbiotic nitrogen fixation is important.

Jackson (1967) reviews many experiments which show indirect effects of H-ion concentration on adsorption and concentration of many inorganic ions. Many investigations have involved the study of H and Ca ion ratios and their effect on Ca adsorption and H-ion toxicity. Jackson (1967) concludes that, in nutrient solution experiments where the bulk solution was circulated to maintain equal composition closely adjacent to the roots, increasing Ca concentration was ineffective in moderating damage from high H-ion concentration.

2. Calcium Deficiency

Jackson (1967) indicates that calcium deficiency does not commonly occur under field conditions and has generally been shown only under very acid conditions ($\text{pH} < 4.0$) or at very low exchangeable Ca levels. Certain crops such as peanuts and tomatoes are exceptions and have shown Ca-deficiency at fairly high Ca concentrations (Colwell and Brady, 1945; Evans and Troxlu, 1953). Results of Loneragan (1960), Joham (1957), and Whitenberg and Joham (1964) show that symbiotic nitrogen fixation, particularly by alfalfa (Medicago sativa) is sensitive to Ca-deficiency.

Absorption and distribution of Ca in plants and the many factors which can influence it have been extensively researched and are reviewed in detail by Jackson (1967). Of particular note, Ca uptake has been shown to be depressed by H, Mn and Al ions. Especially strong depressive effects have occurred in the presence of aluminum ions.

3. Phosphorus Deficiency

Phosphorus deficiency is one of the most common factors contributing

to poor growth of crops on acid soils, and its affect is often attributed to precipitation of insoluble Al and Fe phosphates from soil solution. Another factor at least as important is P deficiency resulting from immobilization of P within the plant by Al ions (Wright, 1943; Wright and Donahue, 1953). Precipitation of P on the epidermal surfaces and within roots, mainly in cell walls, was shown by Wright (1945), Wright and Donahue (1953), Wallihan (1948) and Clarkson (1966). McCormick (1972) using a Mo-blue staining technique has clearly shown the effect of Al on P distribution in plant roots. Phosphorus deficiency resulting from low levels of soluble and labile P in the soil as opposed to that resulting from immobilization within the plant due to Al-toxicity, is at present poorly defined.

Liming generally increases available P as measured by the amount translocated to plant shoots, but there is conflicting evidence as to the effect of liming on soil phosphorus. Adams and Pearson (1967) state that the general concensus is that soon after soluble P fertilizer is added to a soil, it becomes either a Ca-phosphate compound or an Al- or Fe-phosphate compound and subsequent availability depends on the solubility of the compounds formed. In a study of Florida soils, Robertson et al. (1954) found that liming soils high in sesquioxides increased P availability, whereas it had little or no effect on soils low in sesquioxides. Distinct differences in P fixation properties of montmorillonite and vermiculite at various pH and Al saturation levels were shown by Hall and Baker (1971). Montmorillonite fixed increasing amounts of P as pH increased while vermiculite fixed less. Although P adsorption increased as pH was increased in montmorillonite, labile P also increased (labile

P was assessed using an isotope dilution technique with ^{32}P). Murrman and Peech (1969) studied the effects of pH on labile and soluble soil phosphates. Soluble P was considered as that extracted by 0.01M CaCl_2 and labile P was determined by isotopic exchange. Both soluble and labile P were found to reach a minimum at about pH 5.5 and to increase fairly rapidly as pH was increased or decreased from this point. If soluble and labile P decrease on liming up to about pH 5.5, as shown by Murrman and Peech (1969), increased P availability to plants must result mainly from reduced immobilization of P by Al ions. Increased P uptake on liming above pH 5.5 probably results from increased solubility of soil phosphate compounds.

4. Magnesium Deficiency

In some instances poor growth of crops on acid soils is attributed to Mg deficiency. Addition of Ca and K to soils low in Mg may result in Mg deficiency due to their depressing effect on Mg uptake and translocation within the plant (Jackson, 1967). Mulder (1956) compared the effects of $\text{Ca}(\text{NO}_3)_2$ and $(\text{NH}_4)_2\text{SO}_4$ on Mg adsorption and distribution. The superiority of $\text{Ca}(\text{NO}_3)_2$ was attributed both to the beneficial effects of nitrate and the detrimental effects of ammonium on Mg adsorption. In recent greenhouse experiments by Nyborg (personal communication) with some acid soils from Alberta relatively low in Mg, no evidence of Mg deficiency resulted when the soils were amended with $\text{Ca}(\text{OH})_2$ or KOH.

5. Molybdenum Deficiency

Mo deficiencies are commonly reported on acid soils (Jackson, 1967). Reisenauer et al. (1962) reviews a number of papers showing soil

solution Mo to increase with pH. Jackson (1967) indicates that Mo deficiencies are generally overcome by liming, but Foy and Barber (1959) and Gidden and Perkins (1960) have reported Mo responses on limed soils having very low native Mo levels. Anderson and Thomas (1946), Mulder (1948), and Mulder et al. (1959) have shown that nitrogen fixation by legumes is very sensitive to Mo deficiency. At low Mo levels, nodules formed satisfactorily but their N fixing capacity was very low.

6. Aluminum Toxicity

The presence of salt extractable Al in acid soils was first shown by Vietch (1902) but its role in the chemistry of acid soils and clay systems received little attention until the 1950's. Since then Al has been investigated by many workers and the delineation of its importance in the fertility and ion exchange chemistry of acid soils is considered a major advance in soil science (Coleman and Thomas, 1967).

Physiological effects of Al on plant growth have been reported with increasing frequency since the early 1900's. Jackson (1967) cites imprecision of analytical methods and lack of suitable isotopes as reasons for the limited progress in understanding the processes of Al uptake and distribution within plants. Although there are wide differences among plant species and varieties and many inconsistencies are reported, the following outlines general characteristics and effects of Al toxicity:

- (a) In most crop plants, Al accumulates in the roots and little is transported to the above ground portion. Clarkson (1966) reported that 85 - 90% of Al in barley roots was found in cell wall preparations and that this Al was not readily exchangeable with other cations. Clarkson (1966), Sampson et al. (1965), and Rorison (1965)

have shown metabolic effects of Al toxicity, indicating that some Al penetrates into the cytoplasm.

- (b) Immobilization of phosphorus in plants resulting in P deficiency is considered a major factor in Al toxicity. Upon reviewing many results, Jackson (1967) concludes that precipitation of Al-phosphates occurs internally, largely in cell walls and on the epidermal surface of plant roots. Addition of high rates of P to acid soils often overcomes the effects of Al toxicity but the Al content of the shoots is generally not decreased (Jackson, 1967).
- (c) Al toxicity results in restriction of root growth before shoots are effected (Ligon and Pierce, 1932; McLean and Gilbert, 1927; Clarkson, 1965a). Root systems exposed to toxic levels of Al are often described as "stubby or pad-like". This results from failure of main roots and laterals to elongate. Restriction of rooting volume in this manner reduces the plants ability to take up moisture and nutrients. In contrast to Al toxicity which usually effects root growth first, P deficiency usually effects top growth first (Jackson et al., 1964). Distinction between Ca deficiency and Al toxicity have also been noted by Burstrom (1952), Clarkson (1965b), and Sampson et al. (1965). Ca deficiency results in restriction of both cell division and elongation whereas restriction only of cell division has been attributed to Al toxicity.
- (d) The effects of Al on specific metabolic processes has been studied by Sampson et al. (1965), Clarkson (1965a,b; 1966), and Rorison (1965). Results of Clarkson (1965b) and Sampson (1965) indicate

that Al interferes with DNA replication at interphase. Although synthesis of DNA continued after Al treatment, the newly synthesized DNA was of lower molecular weight, and was presumed to be non-genetic material. Rorison (1965) and Clarkson (1966) have also shown that Al pretreatment of roots restricts incorporation of inorganic P into phosphate sugars and into nucleotides.

Al affects the absorption and utilization of many elements. Depression in uptake of P, Ca, Mg, Mn, K, Zn, Fe and Cu have all been reported (Jackson, 1967). Root growth is most severely effected as a result of P deficiency caused by impaired P uptake and translocation.

7. Manganese Toxicity

Two types of Mn toxicity have been noted; one resulting from direct Mn toxicity and the other an indirect effect resulting in Fe deficiency. Jackson (1967) indicated that under field conditions the most common form is direct Mn toxicity. Direct toxicity symptoms and relative tolerance of many species have been described by several workers and are reviewed by Jackson (1967). Black necrotic spots or streaks occur on leaf veins and petioles. Chlorosis on leaf margin and cupping of the leaves is characteristic of Brassica species and legumes.

Page (1961) showed that Mn accumulation occurs mainly in the roots but is translocated to shoots to a greater extent than is Al. Three definite fractions of Mn in roots of oats were shown by Munns et al. (1963). One fraction was readily exchangeable and the other two differed in their rates of transport to shoots and in their rate of isotopic equilibrium with external Mn. Of the two non-exchangeable fractions, the less labile one was concentrated in older regions of the

root and the more labile fraction in the extremities of younger roots.

Many ions have been shown to affect Mn toxicity. Jackson (1967) cites several experiments where Mn uptake was strongly depressed by low levels of Al. Ca and Mg are commonly reported to decrease Mn uptake and K application is shown to increase it. The source of nitrogen influences Mn uptake with higher amounts adsorbed in the presence of NO_3^- than NH_4^+ . With pH carefully controlled, Vlamis and Williams (1962) found that NH_4^+ ions strongly inhibited Mn uptake by barley.

Large variations in Mn content of crops grown on the same soil from year to year have been noted by many workers (Jackson, 1967). Moisture conditions which affect oxidation and reduction of Mn in the soil, light intensity and temperature all influence Mn toxicity. Conditions of high moisture, temperature and light intensity favor Mn toxicity while Al toxicity is most severe under conditions of limited moisture and cool temperatures (Jackson, 1967).

8. Mineralization of Soil Organic Matter

Soil acidity affects many of the processes involved in mineralization of soil organic matter and thereby influences immobilization and transformations of N, P and S (Jackson, 1967). Hallsworth (1958) and Bartholemew and Clark (1965) provide extensive reviews of the effects of acidity on mineralization of organic matter, the development of mycorrhizal associations and symbiotic and non-symbiotic nitrogen fixation. The effect of acidity on ammonification and nitrification resulting in different ratios of NH_4^+ and NO_3^- and its effect on various crop species is discussed by Jackson (1967). Ammonification is less pH sensitive

than nitrification. As illustrated by Cornfield (1952) there is a strong tendency for the NO_3^- to NH_4^+ ratio to become higher as soils become less acid. This can have important agronomic effects since many crop species do not utilize NH_4^+ as well as NO_3^- under acid conditions (Jackson, 1967).

9. Symbiotic N Fixation

Symbiotic N fixation can be separated into three facets:

(a) rhizobia survival and growth, (b) nodulation, and (c) nitrogen fixation. Fred, Baldwin and McCoy (1932) describe the order of sensitivity to acidity of rhizobia cross-inoculation groups as: alfalfa group > pea group > clover group = bean group = soybean group > lupine group. Jackson (1967) indicates that rhizobia survival and growth on acid soils is affected by several components of acidity but H-ion concentration is likely the most critical factor. Results of Norris (1959) and Lonergan and Dowling (1958) showed that the Ca requirements of rhizobia were much lower than those of the host plant. Lonergan (1960) found the Mg requirements for rhizobia growth were approximately eight times greater than for Ca but indicated Mg deficiency would likely occur in the host plant before rhizobia growth would be restricted.

Results of Lonergan and Dowling (1958) show that both Ca and H-ion concentrations affect nodulation. The Ca requirement for infection of the root hair and/or nodule development exceeds that required for normal growth of the host plant.

Jackson (1967) indicates the nitrogen fixation process is especially sensitive to acidity, and that the Ca requirement for N fixation is also higher than that required for normal growth of the

host plant when inorganic nitrogen is supplied. Joham (1957) and Whitenberg and Joham (1964) give evidence indicating that the effect of low Ca supply is indirect, resulting from an insufficient supply of metabolites from the host plant. Anderson and Thomas (1946), Mulder (1948), and Mulder et al. (1959) show that Mo deficiency is often a cause of poor nitrogen fixation by legumes and that it affects only the fixation process. Mo requirements for N fixation exceed those required for normal plant growth when inorganic N is supplied.

C. Diagnosis of Soil Acidity Damage to Plants

A major problem in diagnosing or predicting soil acidity damage stems from the extreme variation among crop species and varieties in their tolerance to the many components of soil acidity. This is well illustrated by results of Foy et al. (1965) showing the relative vegetative yields of six varieties of wheat and of barley grown on a strongly acid soil to range from 1.00 to 0.11 within each species. The relative yield of Thatcher wheat in this study was only 0.12. Management recommendation regarding soil acidity and liming should, therefore, take into account crop species and varieties to be grown.

As indicated by Adams and Pearson (1967), Woodruff (1967), Weeks and Lathwell (1967), and Jackson (1967), the main benefits of liming acid soils result from reduction of toxic Al and Mn and often increased P availability. Traditionally, need for liming is assessed on the basis of pH and per cent base saturation. Estimates of lime requirement usually employ pH measurement plus some estimate of the soils

buffering capacity as indicated by its clay and organic matter content (Woodruff, 1967). In recent years, exchangeable and soluble Al measurements are being studied both as a criteria for predicting acidity damage to the crop and as an index of lime requirement (Kamprath, 1970; Reeves and Sumner, 1970; Evans and Kamprath, 1970; Hutchinson and Hunter, 1970; and Hoyt and Nyborg, 1971). Reeves and Sumner (1970) outline critical values of exchangeable Al for some crop species and indicate that exchangeable Al is a good criteria for predicting crop damage from acidity on soils of similar characteristics. Evans and Kamprath (1970) found that in mineral soils soluble Al was well related to per cent Al saturation of the effective C.E.C., but in organic soils soluble Al was more related to the amount of exchangeable Al than to per cent Al saturation. Hoyt and Nyborg (1971) compared exchangeable Al, 0.01M CaCl_2 -soluble Al, pH and per cent base saturation as indicators of crop response to lime on 40 acid soils. Yield response to liming of rape and alfalfa correlated as well with pH or per cent base saturation as with soluble or exchangeable Al, but barley response was better related to Al than to pH or per cent base saturation.

Soil Mn measurements for predicting crop damage from acidity have been generally less successful as a result of variable soil Mn due to oxidation and reduction reactions. To be available to plants Mn must be in the divalent state. Heat, moisture and drying can all effect the amount of divalent Mn present in soils (Adams and Pearson, 1967). As outlined previously, concentration of other cations in the soil solution can also strongly affect Mn uptake. Hoyt and Nyborg (1971) comparing two methods for exchangeable Mn, two methods for reducible Mn and four

methods for soluble Mn, found that 0.01M CaCl_2 -soluble Mn was better correlated with Mn concentrations in plants than any of the other methods tried. No improvement in the prediction of Mn in barley and alfalfa and only a small improvement for rape was obtained when exchangeable and reducible Mn were included with 0.01M CaCl_2 -soluble Mn in the regression equation.

The question of whether to lime soils to a particular pH level near neutrality or to a level that reduces Al and Mn below critical levels is currently an unresolved issue (McLean and Kamprath, 1970). Many workers such as Hutchinson, Hunter, Kamprath et al., and Reeves and Sumner have shown that maximum yields of most crops can be achieved with adequate fertilization and liming to reduce toxic elements below critical levels (approximately pH 5.5). Others, such as McLean, favor liming to a pH level near neutrality in order that other factors of acidity such as P availability and release of nutrients from mineralization of organic matter are maintained in an optimum pH range.

D. Soil Acidity in the Prairie Provinces

Published research of soil acidity in the Canadian Prairie Provinces is very limited, although in recent years fairly extensive investigations have been conducted in the Peace River region of Alberta and British Columbia by the Canada Department of Agriculture (C.D.A.) Research Station, Beaverlodge. From results of both published and unpublished investigations by researchers at Beaverlodge, it is evident that soil acidity affects crop production on some soils of the Peace

River region. Figures 16, 17 and 18 (p. 34-35) in "Gray Wooded Soils and Their Management", (Bentley et al., 1971) show average responses of several cereal and forage crops to applications of lime on strongly and moderately acid soils of the Peace River region.

Hoyt and Hennig (1962) obtained moderate but significant response to lime in greenhouse and field experiments on Alcan and Nampa soil series of pH (0-6") 6.7 and 6.1, respectively. Significant phosphorus-lime interactions were attributed to increased availability of fertilizer P resulting from lime application. Hoyt et al. (1967) conducted liming experiments with 28 soils from the Peace River region which included soil of the Solonetzic, Luvisolic and Gleysolic orders. Soil pH ranged from 6.8 to 5.3 with a mean of 6.2. Significant yield increase to lime was obtained on 5 and 17 of the soils with Olli barley and alfalfa, respectively. Response of alfalfa and barley to lime was better related to soluble Al (extracted by dilute HCl) than to pH. Hoyt and Nyborg (1971) compared several criteria and methods for predicting crop damage from acidity on 40 acid top soils from the Peace River region. A relatively simple extraction method they developed using 0.01M CaCl_2 was found to be as good or better than other methods used from predicting plant available Al and Mn.

D. K. McBeath (personal communication) conducted a survey of Luvisolic soils in West Central Alberta in relation to alfalfa production. He found that in areas where alfalfa was not grown, soil pH was below 6.0 and in areas where it was grown soil pH was 6.2 or higher. In subsequent growth chambers and field experiments with soils of pH 5.5 or less, response of alfalfa and sweet clover to lime were in the order of

300%. The poor growth of alfalfa and sweet clover on these soils was attributed to nitrogen deficiency resulting from impaired symbiotic nitrogen fixation. On soils of pH less than 5.0, possible Mn toxicity was implicated.

In the Breton Experimental Plots conducted by the University of Alberta since 1930, lime and lime + phosphorus plots have been included among the various fertilizer treatments. Long term yield averages reported in "Gray Wooded Soils and Their Management", (Toogood et al., 1962) show only very small responses to lime or lime + phosphorus on cereals or forage crops. In 1964, the lime + P plot was changed to lime + NPKS. A summary of the yield from 1965 to 1971 showed that on the 5-year rotation of wheat, oats, barley, and 2 years of grass legume hay, wheat yields were increased an average of 32.9% and hay yields 30.7% on lime-NPKS versus NPKS treatments. Yields of barley, the third crop after hay, were increased only 4.2%. Response to lime on these plots appears to be increasing in recent years as the average yield increase of hay from 1969 to 1971 was 91.7%. At least part of the increased lime response noted in the past three years is due to changing the legume species in the rotation from Alsike and Altaswede clover (Trifolium hybridum and Trifolium pratense) and alfalfa (Medicago sativa) to alfalfa only. Soil pH in 1957 as shown in "Gray Wooded Soils and Their Management", (Toogood et al., 1962) indicates NPKS treatments were pH 5.5 as compared to 6.1 for the check and 7.1 for the lime treatments. The increased hay yield on the lime treatment is likely mainly a result of increased nitrogen fixation by the legumes. The increased yields of wheat, the first crop after hay, is evidently also a result of increased nitrogen

fixation since there is very little effect on barley, the third crop after hay. The nitrogen supplied by the NPKS fertilizer treatment is only 10 pounds per acre and therefore would not mask the effect of increased nitrogen resulting from symbiotic fixation. Sulphur deficiency on legume crops is well documented in results from the Breton Plots. The very small lime responses obtained prior to 1964 as compared to those in recent years were at least in part due to sulfur deficiency. (J. A. Toogood and J. A. Robertson - personal communication).

Liming experiments were conducted at the C.D.A. Research Station, Scott, Saskatchewan by H. Ukrainetz since 1964 (personal communication). Application of lime to soils of pH 5.0 to 5.2 resulted in yield increase of wheat and barley in the order of 15 to 20%. Some response was also obtained to applications of gypsum. Soil analysis in 1968, of plots limed in 1963, showed that both $\text{NO}_3\text{-N}$ and $\text{NaHCO}_3\text{-P}$ were higher on limed than unlimed treatments. On unlimed wheat plots, $\text{NaHCO}_3\text{-P}$ was 20 lb. per acre where no fertilizer was applied and 25 lb. per acre on plots receiving P at 17 lb. per acre. On plots limed to pH 7.5, $\text{NaHCO}_3\text{-P}$ was 37 lb. per acre on unfertilized treatments and 51 lb. per acre on P fertilized treatments. Liming appears to have increased available soil P and helped to maintain more of the applied P in an available form. It was indicated that there is a considerable acreage of acid soils in the Scott area.

E. Current and Future Problems and Prospects in Soil Acidity Research

Identifying specific factors involved when crop growth is restricted on acid soils is essential to outlining the most economic

means for their management. Traditional methods of identifying acid soils on the basis of pH and liming to near neutrality can be refined. Long term, detailed experiments are required to assess the benefits of maintaining soils in the neutral range as opposed to liming to reduce toxic elements such as Al and Mn below critical levels. Wide variations among species and varieties in their tolerance to various factors of acidity as shown by Foy et al. (1965) and others suggests opportunities for breeding and selection of resistant varieties. In order that this can be successfully done, specific characterization of both the soil and plant material is essential.

The acidifying effect of nitrogen fertilizer in the ammonium form, or that resulting in the ammonium form upon application to soil is well documented (Adams and Pearson, 1967). The effects of long term application of low rates of ammonium and sulphate on pH of the Breton Plots is shown in "Gray Wooded Soils and Their Management", (Toogood et al., 1962). Since 1964 some of the Breton Plots receive higher rates of nitrogen (in the order of 40 to 60 lb. per acre annually mainly as $(\text{NH}_4)_2\text{SO}_4$) and a more rapid decline in pH is evident (J. A. Toogood and J. A. Robertson - personal communication). Application of nitrogen and sulfur fertilizers to moderately acid Luvisolic soils can cause a fairly rapid decline in pH into the strongly acid range. In the long term, liming or the use of non-acidifying fertilizers will be necessary.

F. Summary

Pearson and Adams (1967), Coleman et al. (1958), and others indicate the most common cause of soil acidity damage to crops results

from Al and Mn toxicity. Phosphorus deficiency whether indirectly, as a result of Al toxicity or due to low available soil phosphorus, is often the most evident cause of poor growth of crops on acid soils. H-ion toxicity and Ca and Mo deficiencies are most commonly implicated as factors affecting reduced nitrogen fixation by legumes on acid soils.

Traditionally, soil acidity problems have been identified by soil pH and per cent base saturation measurements. Acidity was corrected by liming to a pH near neutrality. In many recent studies soil Al and Mn measurements have been assessed as means of predicting soil acidity damage to plants. Liming to reduce Al and Mn levels below critical levels for particular crops has been suggested as an alternative to liming soils to a particular level of pH or base saturation.

Future consideration in soil acidity will likely involve a clearer delineation of soil factors of acidity in relation to plant tolerances and sensitivities. Breeding and selection of crops resistant to acidity holds promise particularly in regions where liming may be impractical due to cost.

METHODS AND MATERIALS

A. Greenhouse Experiment

A pot culture experiment was conducted in the greenhouse for the following purposes: (a) to compare some commonly grown crop species and varieties as to their relative tolerance to soil acidity, and in particular to aluminum and manganese toxicity; and (b) to aid in selection of varieties to use in field experiments.

The soil mixture was a loam in texture with a pH of 5.1, and contained 8 ppm of 0.02M CaCl_2 -soluble aluminum. $\text{Ca}(\text{OH})_2$ was added to achieve a pH of 6.7. The lime requirement was determined by serial addition of $\text{Ca}(\text{OH})_2$ as described under Laboratory Procedures.

A split plot design was used with crops as main plots. Each of the following crops were grown in three replicates on the unlimed soil and on the soil limed to pH 6.7: Olli, Husky, Galt, Bonanza, and Betzes barley (Hordeum vulgare); Glen oats (Avena sativa); Echo and Arlo rape (Brassica campestris); Target and Zephyr rape (Brassica napus); and Ladak, Beaver, Vernal, and Rambler alfalfa (Medicago sativa). In addition, Husky barley; Echo and Target rape; and Beaver and Ladak alfalfa were grown on the limed and unlimed soils to which 100 ppm of manganese as MnCl_2 was added.

Pots with 1.4 kg of soil were used and 100, 40, 45, and 20 ppm of N, P, K, and S, respectively, were added as NH_4NO_3 , KH_2PO_4 , and Na_2SO_4 . One ppm of B as borax and 0.1 ppm of Mo as ammonium molybdate were also added to each pot. Soil was removed from each pot so that

the KH_2PO_4 could be placed in a band one inch below the seeding depth. The soil was replaced, brought to near field capacity and the other chemicals added. All chemicals except the $\text{Ca}(\text{OH})_2$ were added in solution.

Seeds were placed in holes made with a cork borer and covered with quartz sand. The pots were covered and moistened as required until emergence. Alfalfa was thinned to 12 plants per pot and barley, oats, and rape to 7 plants per pot. All crops were watered to field capacity by weight and allowed to approach wilting between waterings. Additional nitrogen as NaNO_3 was added to the cereal crops as required. The alfalfa seed was inoculated and no additional nitrogen was added.

The experiment was conducted from late November, 1970, to the end of May, 1971. Greenhouse temperature controls were set for a maximum and minimum of 18°C to 15°C but temperature ranged well above the maximum during sunny days, particularly in April and May. Illumination from banks of fluorescent lamps was used to obtain a day length of 16 hours.

Barley and oats were harvested after heading, rape at full bloom, and alfalfa in early bloom. Echo and Arlo rape and Olli barley were harvested 58 days after seeding. All other barley and rape varieties and oats were harvested between 70 and 80 days after seeding. The first cut of alfalfa was harvested 81 days after seeding and the third cut grew for 38 days. Plants were harvested, dried at 65°C , and weighed. Barley, oats, and rape were cut at soil level. Alfalfa was cut at 3 cm above soil level to allow more rapid regrowth for subsequent cuts.

B. Field Experiments

Olli and Galt barley (Hordeum vulgare), Span rape (Brassica campestris), Ladak alfalfa (Medicago sativa), and Altaswede red clover (Trifolium pratense) were grown at 28 sites, 14 in the Peace River region and 14 in Central Alberta. At two sites Pendek oats (Avena sativa) were grown in place of Span rape at the farmers request. Approximate site locations are shown in Figure 1; legal locations and soil descriptions are given in Appendix I. The acid condition at the two Innisfail sites was not an inherent characteristic of the soils but resulted from the oxidation of elemental sulphur, which had drifted on to the area from a nearby gass processing plant. For all but three sites, the soils were limed and legumes seeded in the spring or early summer of 1970. The portions of the sites to be used for barley and rapeseed were fallowed and seeded in 1971. The "Valleyview-South" site and the two "Innisfail" sites were limed in fall, 1970, and legumes and cereals sown in spring, 1971. At all sites the lime (Ca(OH)_2) was incorporated to a depth of 6 inches.

1. Soil Sampling

Before lime was applied, all sites were sampled to a depth of either 3 or 4 feet in 6-inch increments to a depth of 1 foot and in 1-foot increments below. Subsequently, composite (0 - 6") samples from limed and unlimed treatments were taken in mid-summer, 1970; fall, 1970; spring, 1971; and fall, 1971. This was done to determine the effect of sampling time on soil pH. All except the initial depth samples were

taken from the barley and rapeseed portion of the plots. The samples were spread thinly on paper to allow rapid drying at room temperature. The air dried samples were ground to pass a 2 mm sieve in preparation for analyses.

2. Experimental Design and Treatments

Field experiments were conducted using a factorial split-plot design with sub-units (crops and nitrogen treatments) in strips. Main plots were "no lime", and "lime" to pH 6.5. Cereals and legumes were randomized in separate blocks using four replications. Each plot consisted of 8 rows, 9 inches apart and 22.5 feet long. All crops were seeded with single row hand pushed seeders. Barley, oats, and rape were fertilized with a blanket application of NPKS at 100, 20, 40, and 17 pounds per acre, respectively. Fertilizer sources were NH_4NO_3 , treble superphosphate, and K_2SO_4 . N, K, and S fertilizers were broadcast and worked in prior to seeding. For barley and oats, all P was drilled with the seed but for rape 10 pounds per acre was drilled with the seed and 10 pounds per acre was banded 1 3/4 inches to the side and 3/4 inches below the seed. Legumes received a blanket application of P, K, S, B, and Mo at 40, 60, 25, 1, and 0.05 pounds per acre, respectively. The first application was broadcast and worked in before seeding. Subsequent applications were surface applied. A "nitrogen" and "no nitrogen" treatment was used for legume crops. The "nitrogen" treatment received 50 pounds N per acre when the legumes were sown, and an additional 100 pounds applied in the fall of 1970 or the spring of 1971. Fertilizer sources for legumes were the same as for cereals except that borax and ammonium molybdate were added. Both the alfalfa and red clover seed was inoculated before seeding.

3. Nodulation Assessment

During late June and early July, 1971, when the first cut of alfalfa was taken, a nodulation assessment was made of both alfalfa and red clover at each site. The nodulation assessment (method outlined by W. A. Rice, C.D.A. Research Station, Beaverlodge) was conducted as follows:

- (a) A portion of row 6 inches long with adjacent soil 6 inches wide and 8 inches deep was dug at 2 locations in each treatment and replicate. The 8 samples for each treatment were then placed on a coarse screen and the soil carefully removed from the roots.
- (b) Nodulation was assessed according to the following criteria by visual estimation.

Nodule color - percentage of pink nodules.

Number of nodules - numerous (> 20/plant).

- several (5 - 20/plant).

- few (< 5/plant).

Nodule size - small (< 3 mm diameter).

- medium (3 - 10 mm diameter).

- large (> 10 mm diameter).

Nodule position - percentage of crown as opposed to

lateral nodules. Nodules on the first 5 cm

of tap root below the cotyledons, or on lat-

erals within 1 cm of this tap root region were

considered as crown nodules.

A numerical ranking of nodulation was made by arbitrarily assigning values to nodule color, number, position, and size as follows:

Color			
% Pink	Score	Number	Score
90-100	4	Several	3
70- 89	3	Numerous	2
50- 69	2	Few	1
30- 49	1	None	0
0- 29	0		

Position			
% Crown	Score	Size	Score
60-100	2	Medium	1
20- 59	1	Small	0
0- 19	0	Large	0

A score of 10 indicates several, medium sized pink nodules, mainly in the crown position. A score of 0 indicates complete lack of nodulation.

4. Harvesting and Yield Determination

At most sites, except those having first year legumes, 2 cuts of alfalfa were taken. In the Peace River region, two cuts of red clover and in Central Alberta one cut of clover was taken. Two and sometimes four (depending on uniformity of stand), 16.5 foot rows were harvested from each treatment. The samples were placed in cotton bags, dried at 60°C, and weighed.

For cereal crops, two 16.5 foot rows were harvested for each treatment. Rape was harvested approximately one inch above soil levels so that both total dry matter and seed yield could be determined. Samples were dried at 60°C, threshed, and weighed.

C. Laboratory Procedures

Most of the methods of soil analysis employed were chosen to compare their usefulness for predicting or identifying soil acidity damage to crops. In choosing methods, consideration was given as to their suitability for routine analysis. Soil reaction (pH) was measured on spring, summer, and fall samples over a two year period to determine the degree of variation with sampling time. Samples taken in spring, 1971, were used to compare various analytical methods for predicting crop response to lime.

1. Soil Reaction (pH)

Determinations were made in 1:2.5 soil-water and soil-1N KCl suspensions. The suspensions were stirred several times during a 30 minute period and then allowed to stand for one hour. A glass electrode pH meter was used. Liquid junction errors were minimized by placing the calomel electrode in the clear supernatant liquid and the glass electrode in the suspension, as suggested by Peech et al. (1953).

2. Exchangeable and Soluble Al and Mn

Exchangeable Al and Mn were extracted with 1N KCl. Twenty g

of soil were shaken with 100 ml of 1N KCl for 30 minutes and filtered under suction using Watman No. 42 paper. Soluble Al and Mn were extracted with 0.02M CaCl_2 . Fifty g of soil were shaken with 100 ml of extractant for one hour and filtered under suction as above. Exchangeable and soluble aluminum were determined by the Aluminon procedure as outlined by Hsu (1963) and modified by Hoyt and Nyborg (1971). Manganese was determined on both extracts with an Atomic Absorption Spectrophotometer.

3. Cation Exchange Capacity and Exchangeable Cations

The above 1N KCl extract was used for determination of Ca, Mg, and Na. Effective cation exchange capacity (C.E.C.) (Coleman and Thompson, 1967) was taken as the sum of the above cations plus exchangeable Al. Percentage base saturation was determined from $\text{Ca} + \text{Mg} / \text{effective C.E.C.}$ For comparative purposes, exchangeable cations and total C.E.C. were also determined on NH_4OAc (at pH 7) extracts from six of the soils. Ammonium saturation was achieved using a method described by Shirlaw (1967). The ASFTL have compared this method with the standard method as outlined by Chapman (1965) and have obtained the same results. Ca, Mg, K, and Na were determined on the NH_4OAc extract with an Atomic Absorption Spectrophotometer. Total C.E.C. was determined by saturation with NaOAc, replacement with NH_4OAc and determined of Na by Atomic Absorption Spectrophotometry.

4. Field Capacity

For the greenhouse experiment, an estimate of field capacity was made by placing 250 cc of soil into $1\frac{1}{2}$ inches diameter plastic tubes. Care was taken to avoid sorting or differential packing. Soil in the tube was compacted by dropping 10 times from a height of one inch. A filter paper was placed on top of the soil column and sufficient water was added to wet the soil column for approximately $\frac{3}{4}$ of its length. The tubes were covered but not sealed to minimize evaporation yet allow free drainage. After 48 hours, the 1 - 2 inch depth was sampled for moisture determination.

5. Lime Requirement

For both the greenhouse and field experiments, lime requirements were determined by equilibration with Ca(OH)_2 . To 20 g of soil and 50 ml of water, serial additions of Ca(OH)_2 were made. The suspension was shaken occasionally for 3 days to ensure adequate mixing and to maintain aerobic conditions. Lime requirements were calculated from the amount of Ca(OH)_2 required to attain a pH of 6.5.

D. Statistical Analysis

Analyses of variance were conducted on yield data from field and greenhouse experiments. The factorial split-plot design with sub-units (crops or N treatments) in strips used for the field experiments was chosen out of necessity and practicality in conducting the

experiments. However, this design sacrificed precision on the main effects (lime and crops or N treatments) in order to provide higher precision on the interaction (Cochrane and Cox, 1957). In addition, the design did not always lend itself to individual treatment comparisons. If the overall effect of lime was not significant, the effect of lime on individual varieties or N treatments could not be compared. Since the effect of lime on individual treatments was of primary interest, the data was also analyzed as a randomized complete block design. The treatments for a particular crop (i.e., Barley: Olli - "lime", Olli - "no lime", Galt - "lime", and Galt - "no lime") were analyzed as occurring individually at random in a complete block design. In the design used, randomization was incomplete in that lime and varieties or nitrogen treatments were maintained as units. However, additional important comparisons were made possible by using the randomized complete block analysis and it was felt that the lack of complete randomization did not seriously jeopardize the results. Duncan's Multiple Range Test were used to compare the treatment means for the randomized block analysis.

Correlation and regression analyses were conducted to compare yield response to lime with various soil criteria. For all correlation and regression analyses, yield data was expressed as per cent yield calculated as the yield of "no lime" treatments as a percentage of the yield of "lime" treatments.

RESULTS AND DISCUSSION

A. Greenhouse Experiment

Five varieties of barley (Hordeum vulgare), one of oats (Avena sativa), four of rape (Brassica campestris and Brassica napus) and four of alfalfa (Medicago sativa) were grown on a limed and unlimed acid soil known to contain sufficient soluble aluminum to be toxic to sensitive crops. In addition, Husky barley, Echo and Target rape, and Ladak and Beaver alfalfa were grown on the same limed and unlimed soil to which 100 ppm of manganese as MnCl_2 was added. Vegetative yields were taken as a measure of tolerance of species and varieties to soil acidity, and in particular their tolerance to Al and Mn toxicity. The results provided information for selecting the crops and varieties used in the field experiments, and enabled the results of the field experiment to be interpreted to other varieties.

Soil Characteristics and Lime Response

Soil analyses of pH, 0.02M CaCl_2 -soluble and 1N KCl-exchangeable aluminum and manganese are presented in Table 1. In the unlimed soil, exchangeable and soluble Al were 232 and 8.2 ppm, respectively, and did not differ greatly among determinations on the moist, air dried and original soil. The 36.6 and 5.3 ppm of exchangeable and soluble Mn determined on the soil treated with 100 ppm of MnCl_2 indicates that much of the added Mn was no longer in an exchangeable or soluble form at the end of the experiment. Barley, oats and rape were harvested at the late

Table 1. Analyses of Soil From the Greenhouse Experiment

Soil	Treatment	pH in Water	Aluminum		Manganese	
			Exchangeable (ppm)	Soluble (ppm)	Exchangeable (ppm)	Soluble (ppm)
Original soil	No Lime	5.0	232	8.2	--	1.0
Moist soil from pots on completion of the experiment	Lime	6.7	0.0	0.0	1.8	1.6
	Lime + Mn	6.5	0.0	0.0	9.1	2.0
	No Lime	5.4	240	8.5	3.6	3.5
	No Lime + Mn	5.4	243	7.7	36.6	5.3
Air dried soil from pots on completion of the experiment	Lime	6.5	0.0	0.0	--	--
	Lime + Mn	6.4	0.0	0.0	--	--
	No Lime	5.2	242	8.7	--	1.8
	No Lime + Mn	5.2	--	--	--	--

Exchangeable Al and Mn -- 1/2 hour extraction with 1N KCl.

Soluble Al and Mn -- 1 hour extraction with 0.02M CaCl_2 .

bloom stage and alfalfa at the early bloom stage. Highly significant responses to lime (Tables 2 and 3) were obtained for all crops except oats which is known to be tolerant to acidity. No significant effect resulted from the addition of 100 ppm of Mn on any of the crops although some yield reduction from Mn occurred on all the crops, except on the third cut of alfalfa. In the case of Echo rape, yield reduction from Mn was very nearly significant at the 5% level (Table 2). On the third cut of alfalfa, small yield increases occurred on the Mn treatments and visual symptoms of Mn toxicity were no longer evident. On the first cut of alfalfa (Plate 1) severe Mn toxicity symptoms were evident.



Plate 1. Alfalfa on the left showing Mn toxicity symptoms induced when 100 ppm of MnCl_2 was added to the soil and on the right normal leaves of alfalfa grown on the soil with both Mn and lime added.

Table 2. Dry Matter Yield and Percent Yield of Barley, Oats, and Rape Varieties Grown on a Limed and Unlimed Acid Soil in a Greenhouse Pot Experiment

Crop	Variety	Yield of Dry Matter Treatment		% Yield (No Lime x 100/Lime)
		No Lime (g/pot) ¹	Lime (g/pot) ¹	
Barley	Olli	9.11	10.68**	85.3
	Husky	10.79	14.15**	76.2
	Husky + Mn	10.57	13.64**	77.5
	Galt	10.39	14.20**	73.2
	Betzes	14.32	16.49**	86.8
	Bonanza	10.23	12.10**	84.5
Oats	Glen	9.64	10.22	94.5
Rape	Echo	7.15	8.51**	84.0
	Echo + Mn	6.29	8.42**	74.7
	Arlo	6.39	8.43**	75.8
	Target	9.90	11.64**	85.0
	Target + Mn	9.71	11.77**	82.4
	Zephyr	10.83	12.89**	84.0
Mean		9.64	11.78**	
Least Significant Difference				
Level of Significance		Lime	Lime on One Variety	Varieties at One Level of Lime
5%		0.43	0.91	0.88
1%		0.99	1.31	1.34

¹ Average of 3 replicates.

** Indicates significance of lime response at the 1% level.

Table 3. Dry Matter Yield and Percent Yield of Four Alfalfa Varieties Grown on a Limed and Unlimed Acid Soil in a Greenhouse Pot Experiment

Variety	Yield of Dry Matter Treatment		% Yield (No Lime x 100/Lime)
	No Lime ¹ (g/pot) ¹	Lime ¹ (g/pot) ¹	
<u>First Cut</u>			
Ladak	2.09	5.28**	39.6
Ladak + Mn	1.73	5.11**	33.9
Beaver	1.82	4.62**	39.4
Beaver + Mn	1.36	4.41**	30.8
Vernal	1.87	4.93**	37.9
Rambler	1.62	4.76**	34.0
Mean	1.75	4.85**	
<u>Third Cut</u>			
Ladak	0.43	5.07**	8.5
Ladak + Mn	0.59	5.08**	11.6
Beaver	0.50	5.77**	8.7
Beaver + Mn	0.65	5.74**	11.3
Vernal	0.56	5.70**	9.8
Rambler	0.57	5.69**	10.0
Mean	0.55	5.51**	
<u>Least Significant Difference</u>			
Level of Significance		Lime	Varieties at One Level of Lime
First Cut:	5%	0.27	0.73
	1%	0.62	1.03
Third Cut:	5%	1.30	1.34
	1%	2.98	2.55

¹ Average of 3 replicates.

** Indicates significance of lime response at the 1% level.

Manganese toxicity symptoms were also evident on all varieties of rape. The level of soluble Mn (5.3 ppm) found in the "no lime plus Mn" treatments on completion of the experiment is below the level considered toxic (Hoyt and Nyborg, 1971). The level of manganese apparently decreased with time and reached a non-toxic level toward the end of the experiment. As a result, it is not possible to indicate a level of Mn which would produce a significant yield reduction in the various crops grown.

Tolerance of Species and Varieties to Soil Acidity

The percent yield (no lime treatments as a percentage of lime treatments) of the crops was used to compare their relative acidity tolerance. Comparing the four species grown, tolerance to acidity was in the order oats > rape = barley >> alfalfa. Rape is regarded to be more tolerant to Al toxicity and less tolerant to Mn toxicity than barley (Hoyt and Nyborg, 1972). The results indicated that Al tolerance of barley and rape are of the same order, with as much difference occurring among varieties as between the two species. Although significant yield reduction did not occur from the Mn treatments, rape yields were reduced more than barley yields.

The data in Tables 2 and 3 show that alfalfa is much more sensitive to soil acidity than oats, barley or rape. Even when adequate nitrogen and other nutrients were supplied (results of first cut), growth of alfalfa was greatly reduced on the unlimed soil. Additional nitrogen was not added after the first cut so that subsequent growth

became dependent on symbiotic nitrogen fixation. Due to differences in rates of growth between treatments, the nitrogen supply was depleted at different stages on the second cut and the results could not be used. The unlimed soil produced very low yields on the third cut, indicating that little or no nitrogen fixation took place. Severe manganese toxicity symptoms occurred on the "no lime plus Mn" treatments (first cut), but the yield reduction from Mn was not significant. This is in contrast to results of Ouellette and Dessureaux (1958), and Hewitt (1948) who have obtained yield reduction of alfalfa from both Mn and Al. Hewitt (1948) found that Al and Mn together reduced yield of alfalfa to a greater degree than either Al or Mn alone whereas with barley, Al alone caused a greater yield reduction than Al and Mn together. However, in summarizing the results of many workers, Jackson (1967) indicates that Al toxicity has often been overlooked as a cause of poor growth of crops on acid soil because Mn toxicity has been more apparent.

Sizable differences in relative yields occurred among the barley varieties. The greater acidity tolerance of Olli as compared to Husky barley is consistent with results obtained by P. B. Hoyt and M. Nyborg (personal communication). The data indicated that the varieties Galt and Husky are more sensitive to Al toxicity than are Olli, Betzes and Bonanza. Foy et al. (1965) found relative Al tolerances of barley varieties ranging from 0.11 to 1.00 when grown in nutrient solution, indicating there is a wider range in Al tolerance of barley varieties than is shown in the five varieties used in this experiment.

The Al tolerance of Echo, Target and Zephyr rape appears similar to that of the more tolerant barley varieties. The percent yield of Arlo rape was similar to the more acid sensitive barley varieties, Husky and Galt. No difference in tolerance to acidity was evident among the alfalfa varieties. Ouellette and Dessureaux (1958) have found differences in both Al and Mn tolerance among alfalfa clones.

The addition of 100 ppm of Mn to the soil caused a greater reduction in yield of Echo than of Target rape. However, the decline in the soil Mn level that occurred as the experiment progressed could have caused this difference. Target rape is a later maturing variety than Echo and therefore may have been subject to lower soil Mn levels at similar growth stages.

In summary, the results of the greenhouse experiment showed that lime increased the yields of barley and rape and greatly increased the yield of alfalfa on a soil of pH 5.0 with 8 ppm of CaCl_2 -soluble aluminum. Some varietal differences in Al tolerance are evident in the barley and rape varieties but no differences in acidity tolerance are evident among the alfalfa varieties. Addition of 100 ppm of Mn to the soil resulted in visual Mn toxicity symptoms on alfalfa and rape but did not produce statistically significant reductions in yield.

B. Soil Analyses

General Soil Characteristics

Soil samples taken from 28 field sites were analyzed and results are presented in Appendix II and III. The soils ranged widely

in both surface (0 - 6") and sub-surface pH. The Dark Brown and Black Solodic and Solonetzic soils such as those at the Raessler, Lyster and Valleyview North sites had strongly acid surface horizons but pH increased rapidly with depth (Appendix II). In contrast, pH decreased with depth to 3 feet at the Dyck, Derksen and Silver Valley sites. At several other sites the lowest pH occurred in the 6 - 12" depth (upper B horizon).

The acid soil condition at the two Innisfail sites resulted from the oxidation of elemental sulphur which drifted on to the field from a nearby natural gas processing plant. The Innisfail South site was extremely acid (pH 3.4) and was devoid of all vegetation except where lime was applied. Soil pH (0 - 6") of the other sites ranged from 4.5 at Silver Valley to 6.1 at Cooking Lake. Soluble aluminum values ranged from 0 to 152 ppm, but were not well distributed over the entire range (Table 4). Only 6 of the sites had greater than 2.0 ppm of CaCl_2 -soluble aluminum. Two of the sites, Innisfail South and Silver Valley have very high levels of soluble aluminum, with 152 and 45 ppm, respectively. Soluble manganese levels are fairly low at most sites. Greater than 20 ppm of soluble manganese occurred at only 4 of the sites.

Seasonal Variation in Soil pH

Determinations of pH on samples taken in the spring, summer and fall during a two-year period showed only small variation with time of sampling (Table 5). Over the two-year period, soil pH changed

Table 4. Average and Range of Several Soil Characteristics for 28 Field Sites

Characteristic	Average	Range
Soluble Al (ppm)	8.4 (3.1) ¹	0 to 152
Soluble Mn (ppm)	14.5 (10.2) ¹	2 to 132
Exchangeable Al (ppm)	77.9	0 to 670
% Base Saturation (KCl extraction)	90	41 to 99
pH in Water	5.3	3.4 to 6.1
pH in KCl	4.2	3.1 to 5.2
Lime Requirement (cwt/acre of Ca(OH) ₂ to pH 6.5)	63.0	8.6 to 170

¹ Average with Innisfail South site omitted.

Table 5. Seasonal Variation in Soil pH at 20 Field Sites

Treatment	Average pH of 20 Field Sites at Different Times of Sampling					Maximum Difference
	Spring 1970	Summer 1970	Fall 1970	Spring 1971	Fall 1971	
No Lime	5.46	5.38	5.34	5.38	5.30	0.16
Lime	--	6.58	6.56	6.53	6.50	0.08

by greater than 0.3 units at only 2 of the 28 sites (Appendix IV). The maximum difference in average pH among the various spring, summer and fall samplings was 0.16 for the unlimed soils and 0.08 for the limed soils. The greatest difference occurred at the Bertsch site where the first sampling was 0.7 units higher than at any other sampling time. A small difference in sampling depth achieved with different sampling tools may have caused this relatively large change in pH because pH increases rapidly with depth at this site. Seasonal variations in pH obtained in this study are smaller than those reported by Bowser and Leat (1958). They found that the pH of the Ap horizon of a Luvisolic soil (Cooking Lake series) ranged from 7.7 to 6.8 during the growing season. In this study, the magnitude of the seasonal variation in pH was not large enough to seriously affect its use as an index of soil acidity.

Lime Requirement and Percentage Base Saturation

The rate of lime required to obtain a pH of 6.5 in the 0 - 6" depth ranged from 8.6 to 170 cwt per acre (Appendix III). At the Horen site 28.0 cwt of Ca(OH)_2 raised the pH from 5.3 to 6.4 whereas at the Lowie site 58.6 cwt of Ca(OH)_2 only increased pH from 5.8 to 6.6. The more highly leached soils (Gray Luvisols, Solodic Gray Luvisols and Gray Solods) required an average of 41.2 cwt of Ca(OH)_2 to increase pH by 1 unit, whereas the Dark Gray, Black, Brown and Gleysolic soils required an average of 58.6 cwt to increase pH by 1 unit. Soil pH alone did not provide a good index of lime requirement.

The relationship between pH and percentage base saturation of soils has been studied extensively and is discussed in detail by Coleman and Thomas (1967). The soils in this study are generally more highly base saturated than is commonly found in acid soils (Appendix III). The average percentage base saturation ($\text{Ca} + \text{Mg} \times 100 / \text{total cations}$) of the 28 soils used in this study is 90 (Table 4), and at only one site (Silver Valley) was the base saturation less than 50%.

Percentage base saturation, determined by extraction with ammonium acetate at pH 7 on a few of the soils, gave lower values than those obtained by the KCl extraction (Appendix III) but again only the Silver Valley soil was below 50% base saturation. Based on the discussion of Coleman and Thomas (1967), the high base saturation of these soils relative to pH indicates that permanent charge accounts for much of the cation exchange capacity.

C. Crop Response to Lime

Crop response to lime varied widely among the crops grown (Table 6). Alfalfa was the least acid tolerant crop and significant yield responses to lime were obtained at 21 of the 26 sites where it was grown. In contrast, significant responses to lime on red clover were obtained at only 5 sites. Olli and Galt barley differed in their response to lime. Galt showed a statistically significant response at 9 of 26 sites, while Olli gave a significant response at only 2 sites. Although not statistically significant, barley yields were increased by liming at most sites.

Table 6. Yields of Barley, Rape, Alfalfa, and Red Clover
from 28 Field Experiments

Site	Treatment	Barley ¹		Rape ²		Alfalfa ¹		Red Clover ¹	
		Galt	Olli	Seed	Straw	(+N)	(-N)	(+N)	(-N)
		Yield in cwt per acre							
<u>Central Alberta</u>									
Raessler	Lime	31.0a	27.8ab	15.2a	47.8a	66.5a	65.7a	39.5ab	46.0a
	No Lime	25.6b	25.6b	13.3a	41.9a	46.7b	42.2b	39.9ab	33.5b
Bertsch	Lime	28.7a	25.4a	14.3a	42.1a	48.2a	48.0a	31.8a	35.2a
	No Lime	27.6a	24.2a	11.8a	38.8a	42.8a	33.9a	36.2a	33.7a
Hepp	Lime	24.3a	21.1a	8.6a	39.0a	32.0a	32.7a	--	--
	No Lime	20.9a	19.6a	7.0a	29.9a	29.2a	17.2b	--	--
Lyster	Lime	30.1a	28.5a	31.8a*	--	16.9b	21.3a	--	--
	No Lime	23.2b	26.5ab	30.6a*	--	11.2b	14.9b	--	--
Kay	Lime	34.6a	28.8bc	21.9a	77.7a	47.9a	43.5a	--	--
	No Lime	31.5b	26.3c	16.1b	62.0b	37.1b	29.8c	--	--
Innisfail North	Lime	39.0a	29.6b	14.2a	47.4a	15.1a	15.2a	--	--
	No Lime	38.2a	30.5b	13.5a	44.0a	14.0a	14.8a	--	--
Innisfail South	Lime	36.6a	22.6b	13.8a	44.2a	--	--	--	--
	No Lime	0.0c	0.0c	0.0b	0.0b	--	--	--	--

* Glen oats grown in place of rape.

Table 6. (Continued)

Site	Treatment	Yield in cwt per acre							
		Barley ¹		Rape ²		Alfalfa ¹		Red Clover ¹	
		Galt	Olli	Seed	Straw	(+N)	(-N)	(+N)	(-N)
Cormie	Lime	28.3a	23.8ab	20.3a	65.0a	56.8a	56.9a	46.4a	45.0a
	No Lime	23.3ab	21.6b	18.3a	57.7a	43.8b	18.8c	41.7a	41.6a
Horen	Lime	--	--	--	--	60.9a	63.5a	40.5a	36.2a
	No Lime	--	--	--	--	46.6ab	24.9b	50.2a	47.2a
Weist	Lime	34.6a	27.8bc	17.0a	63.2a	66.6a	61.6a	45.8a	48.8a
	No Lime	30.5b	24.2c	14.4a	57.0a	39.4b	25.4b	46.6a	48.2a
Webster	Lime	48.7a	24.6b	14.5a	66.6a	91.5a	84.2a	53.7a	56.4a
	No Lime	45.7a	21.3b	14.1a	62.4a	62.6b	61.9b	52.3a	60.6a
Lowie	Lime	--	--	--	--	76.8a	64.9ab	--	--
	No Lime	--	--	--	--	60.9b	56.4b	--	--
Cooking Lake	Lime	28.8a	21.2b	8.3a	55.0a	75.2a	72.6a	91.1a	99.5a
	No Lime	30.8a	23.5b	9.0a	58.7a	78.1a	76.9a	74.0b	78.1b
Williams	Lime	43.1a	31.4b	19.9a	65.9a	50.3b	54.2a	43.6a	42.5a
	No Lime	41.9a	32.7b	17.8a	63.9a	39.3c	37.0c	40.4a	40.7a
<u>Peace River Region</u>									
Valleyview North	Lime	35.2a	26.4b	11.3a	49.8a	34.8a	34.3a	18.1a	18.3a
	No Lime	30.3ab	25.6b	12.2a	46.3a	26.8b	13.2c	20.2a	19.7a
Valleyview South	Lime	30.9a	27.7ab	12.3a	50.4a	13.3a	12.2a	8.4b	7.5b
	No Lime	24.0b	24.9b	13.7a	50.4a	12.8a	4.0b	10.4a	7.0b

Table 6. (Continued)

Site	Treatment	Yield in cwt per acre									
		Barley ¹		Rape ²		Alfalfa ¹		Red Clover ¹			
		Galt	Olli	Seed	Straw	(+N)	(-N)	(+N)	(-N)		
Derksen	Lime	35.9a	24.5b	13.0a	--	58.9a	57.5a	64.2a	60.8a		
	No Lime	32.8a	22.6b	12.8a	--	26.7b	10.7c	56.6b	53.1b		
Dyck	Lime	29.4a	25.8ab	12.6a	--	48.6a	43.7a	52.4a	53.7a		
	No Lime	21.4b	22.1ab	11.8a	--	27.5b	15.4c	42.9a	31.0a		
Wanham	Lime	33.2a	24.2b	11.5a	47.4a	41.0a	36.6a	27.2a	27.6a		
	No Lime	35.0a	24.8b	14.2a	52.7a	17.7b	8.8c	28.9a	27.1a		
Spirit River	Lime	32.3a	22.7b	14.6a	53.8a	60.7a	56.4a	47.3a	47.8a		
	No Lime	30.3a	20.8b	15.1a	54.7a	46.4b	35.1c	51.5a	50.8a		
Silver Valley	Lime	36.7a	16.8b	2.9a	36.5a	29.5a	27.8a	24.1a	28.5a		
	No Lime	2.8c	7.4c	1.9a	15.2b	0.0b	0.0b	0.0b	0.0b		
Fourth Creek	Lime	36.3a	26.6b	12.7a	58.7a	--	--	--	--		
	No Lime	34.5a	32.7ab	13.9a	51.4a	--	--	--	--		
Wembley	Lime	48.5a	31.8b	13.3a	55.6a	55.4a	44.1a	23.4a	19.4b		
	No Lime	44.4a	30.2b	14.1a	55.3a	44.9a	41.4a	22.1ab	23.2a		
Border	Lime	37.9a	25.9b	12.3a	44.7a	40.6a	35.2a	27.8a	31.1a		
	No Lime	32.3ab	26.3b	9.7a	38.6a	36.9a	17.2b	31.4a	34.1a		
Bessborough	Lime	33.1a	30.7a	12.0	41.7	33.1a	31.8a	16.5a	19.7a		
	No Lime	32.9a	28.4a	12.3	46.3	22.6b	16.8b	15.7a	18.2a		

Table 6. (Continued)

Site	Treatment	Yield in cwt per acre							
		Barley ¹		Rape ²		Alfalfa ¹		Red Clover ¹	
		Galt	Olli	Seed	Straw	(+N)	(-N)	(+N)	(-N)
Prespatou	Lime	28.9a	28.5a	14.5a	50.7a	80.4a	80.2a	77.3a	67.1a
	No Lime	16.4b	25.4a	14.8a	51.4a	29.7b	2.2c	61.6ab	47.7b
Hastings	Lime	17.7a	19.9a	13.8a	54.9a	76.7a	73.2ab	63.4a	59.4a
	No Lime	18.3a	20.1a	13.3a	56.9a	77.5a	64.4b	61.3a	57.7a
Buick Creek	Lime	29.6a	28.4a	11.6a	38.6a	48.9a	51.1a	51.8a	51.7a
	No Lime	30.3a	25.7a	11.4a	36.5a	11.6b	14.7b	58.8a	54.5a

¹For barley, alfalfa, and red clover the four treatment means within crops followed by the same letter are not significantly different by Duncan's multiple range test at $p = 0.05$.

²For rapeseed and rape straw, two treatment means (lime and no lime) followed by the same letter are not significantly different from one another.

Rape showed a significant response to lime at only 2 sites (Table 6). Wind and heavy rain caused early lodging of rape at many of the sites in the Peace River region. Yields were somewhat erratic and yield decreases from lime resulted at several sites. The heavier growth and advanced maturity of the lime treatments noted at some sites may have resulted in greater lodging and seed shattering on these as compared to the "no lime" treatments. Straw yields for rape (Table 6) gave less erratic results than seed yields but even the straw yield on the lime treatments were lower than "no lime" treatments at some sites.

Alfalfa

Yield increases obtained from liming on alfalfa without applied nitrogen are summarized in Table 7. The average yield increase from lime over all sites was 22.1 cwt per acre and even on moderately acid soils (pH 5.6 - 6.0) substantial yield increases (15.8 cwt per acre) were obtained. Application of 100 lb. per acre of nitrogen increased alfalfa yield significantly on "no lime" treatments at 12 sites but the average yield increase from nitrogen was only 9.0 cwt per acre, as compared to 22.1 cwt per acre increase from lime. Three reasons are suggested as to why nitrogen response was substantially less than the lime response: (i) nitrogen applied at 100 lb. per acre was insufficient to supply the needs of the crop for two cuts; (ii) at sites where pH was below 5.5, alfalfa yields were reduced by factors other than impaired symbiotic nitrogen fixation (i.e. aluminum toxicity); and

(iii) at some sites nitrogen application caused increased competition from weeds and grasses and therefore was not as effective as symbiotic nitrogen fixation in supplying nitrogen to the alfalfa. At several sites, little or no response to nitrogen was obtained. At the Lyster site, nitrogen reduced yields on both the "lime" and "no lime" treatments, probably as a result of increased weed competition.

Table 7. Yield Increase of Alfalfa from Lime and Nitrogen on Soils in Various pH Ranges

pH Range	No. of Sites	Yield Increase from Lime (cwt per acre)		Yield Increase from Nitrogen (cwt per acre)	
		Mean	Range	Mean	Range
pH < 5.0	5	40.9	23.8 to 78.0	12.0	0 to 27.5
5.1 - 5.5	13	20.0	0.4 to 38.6	11.3	-3.7 to 25.0
5.6 - 6.0	7	15.8	2.7 to 36.4	3.8	-3.1 to 36.4
pH > 6.0	1	-4.3	--	1.2	--
Average Increase		22.1		9.0	

Alfalfa at the Innisfail North site was seeded in spring, 1971, and did not respond to nitrogen or lime (Table 6). The available nitrogen level in this soil was likely adequate for alfalfa during the year of establishment and additional nitrogen from fertilizer or symbiotic fixation was not required. Alfalfa at the Webster, Williams and Buick Creek sites did not respond to applied nitrogen but did respond

to lime. The reason for the lack of nitrogen response at the above sites is not evident because the soils are in the pH range 5.5 to 6.0, where impaired symbiotic nitrogen fixation would be expected to be the main reason for poor alfalfa growth.

The yield of limed alfalfa at the Silver Valley site is relatively low indicating that subsoil acidity may have reduced the yield. Using soil from the Silver Valley site, R. C. McKenzie (1972 -- personal communication) has shown in greenhouse experiments that subsoil acidity restricts rooting depth of alfalfa. Subsoils at the Dyck and Derksen sites are also strongly acid but alfalfa yields are relatively high. Available moisture is likely an important factor governing the degree to which subsoil acidity restricts yields. When a crop is dependent on subsoil moisture reserves, subsoil acidity will likely reduce yields.

The responsiveness of alfalfa to lime has been demonstrated by many workers and is borne out by the results in this study. Adams and Pearson (1967) indicate that alfalfa is likely the most responsive crop to lime. Yield increases from lime were obtained at the Williams (pH 6.0) and Lowie (pH 5.8) sites. Weeks and Lathwell (1967) outline data showing alfalfa response to lime up to pH 6.6. Alfalfa response to lime in the pH range 5.5 to 6.5 likely results from improved symbiotic nitrogen fixation, since toxic levels of Al and Mn are not present. Fred, Baldwin and McCoy (1932) indicate that the alfalfa cross-inoculation group of rhizobia are the most acid sensitive.

Red Clover

Response of red clover to lime occurred only when pH was 5.0 or less, except in one case (Table 6). Red clover at the Cooking Lake site (pH 6.1) showed a significant response to lime, but visual observation indicated this was due to stand variation caused by winter killing. The yield decrease from lime obtained at the Horen site was also due to stand variation. A large yield increase (22.7 cwt per acre) was obtained at the Dyck site (pH 4.5) but it was not significant because of large variations among replicates. The average yield increase from lime on red clover was only 4.5 cwt per acre as compared to 22.1 cwt on alfalfa. Satisfactory stands of red clover were not established at the Hepp, Lyster and Kay sites in East Central Alberta due to drought and weed competition.

In considering the use of red clover as an alternative to liming soil to allow alfalfa production, the results indicate the following: (i) At the five sites in East Central Alberta, red clover was difficult to establish and yielded poorly. Its lack of drought tolerance makes it an unsuitable alternative to alfalfa in this area. (ii) Omitting the 5 sites in East Central Alberta and those of pH ≤ 5.0 where red clover responded to lime, the average yield (15 sites) of red clover without lime was 40.6 cwt compared to 51.2 cwt for limed alfalfa (Table 8). In areas other than East Central Alberta, red clover produced satisfactory yields on soils of pH > 5.0 and is a useful alternative to liming soils for alfalfa production. However, at most sites, limed alfalfa produced substantially higher yields than red clover.

Table 8. A Comparison of Alfalfa Yields on Limed Soils with Red Clover Yields on Unlimed Soil from 15 Sites

Site	pH of Unlimed Soil	Alfalfa Lime (-N) (cwt/acre)	Red Clover No Lime (-N) (cwt/acre)
Cormie	5.1	56.9	41.6
Horen	5.3	63.5	47.5
Wanham	5.4	36.6	27.1
Spirit River	5.4	56.4	50.8
Valleyview North	5.4	34.3	19.7
Border	5.5	35.2	34.1
Weist	5.5	61.6	48.2
Valleyview South	5.5	12.2	7.0
Webster	5.6	84.2	60.6
Bessborough	5.6	31.8	18.2
Buick Creek	5.6	51.1	54.5
Hastings	5.8	73.2	57.7
Wembley	5.9	44.1	23.2
Williams	6.0	54.2	40.7
Cooking Lake	6.1	72.6	78.1
Average	5.6	51.2	40.6

In summary, the results of this study show that red clover is much more tolerant to acidity than alfalfa. Significant yield increases of red clover from lime did not occur unless soil pH reached 5.0 or less. Although red clover is considered to be more acid tolerant than alfalfa, Woodruff (1967) lists red clover in the least acid tolerant group of crops and indicates that the permissible pH range for satisfactory growth is 6.0 to 7.5. Adams and Pearson (1967) in reviewing results of several investigations state that red clover yields are reduced by acidity below the pH range 5.5 to 6.5. The results of this study show that red clover is more acid tolerant than is generally reported in the literature.

Barley

Yield increases of Galt and Olli barley are summarized in Table 9. A substantial difference in yield response to lime between the two varieties is evident, particularly on the more acid soils ($\text{pH} \leq 5.0$). The average yield increase from lime on Galt at 19 sites ($\text{pH} \leq 5.5$) was 7.6 cwt per acre as compared to 2.8 cwt for Olli. The greater acidity tolerance of Olli as compared to Galt shown here is consistent with results of the greenhouse experiment. However, the low yield potential of Olli barley distracts from its usefulness as an acid tolerant barley variety. On unlimed soils of $\text{pH} \leq 5.5$ (19 sites) Galt barley yielded 25.3 cwt per acre as compared to 22.7 cwt per acre for Olli. Only on very strongly acid soils ($\text{pH} \leq 5.0$) did Olli show any yield advantage over Galt (Olli and Galt yields were 22.6 and 22.2 cwt/acre, respectively).

Table 9. Yield Increase of Galt and Olli Barley from Lime on Soils in Various pH Ranges

pH Range	No. of Sites	Yield Increase from Lime			
		Galt		Olli	
		Mean (cwt/acre)	Range (cwt/acre)	Mean (cwt/acre)	Range (cwt/acre)
pH $\leq$ 5.0	7	14.5	1.8 to 36.6	5.3	-6.1 to 22.6
5.1 - 5.5	12	3.5	-1.8 to 6.9	1.4	-0.9 to 3.6
5.6 - 6.0	6	1.2	-0.1 to -4.1	1.4	-1.3 to 3.3
pH $>$ 6.0	1	-2.0	--	2.3	--
Average increase	26	5.7		2.5	

Generally, the data show that barley gave substantial yield increases from lime on soils of pH $\leq$ 5.0 and moderate yield increases on soils of pH 5.1 to 5.5. Little or no lime response was obtained on soils of pH $>$ 5.5. As indicated in the greenhouse experiment, the varieties Galt and Olli represent the range in acidity tolerance found in commonly grown varieties in Alberta. The varieties Betzes and Bonanza may be more useful than Olli as acid tolerant varieties because they were as acidity tolerant as Olli and have a higher yield potential. The wide range in acidity tolerance of barley varieties reported by Foy et al. (1965) indicates a good potential for the development of suitable varieties with greater acidity tolerance.

Rape

Rapeseed yields on "no lime" treatment were greater than on the "lime" treatment at 8 of the 14 sites in the Peace River region indicating that lodging and seed shattering was greater on "lime" than on "no lime" treatments at many sites (Table 6). In the greenhouse experiment, yields of Echo rape and Olli barley were similar when grown on an acid soil (pH 5.0) which contained 8.0 ppm of soluble aluminum. Comparing the yield of Span rape straw with Olli barley from 18 field experiments, the relative yields are 86% and 87%, respectively. There is an indication that, at sites such as "Raessler" and "Hepp" which contained 24 and 16 ppm of soluble manganese, respectively, that manganese toxicity reduced yields of rape.

Because the rapeseed yields were somewhat erratic, the data does not provide a clear delineation of its response to lime. However, the data from the greenhouse and field experiments indicate that the rape varieties Echo and Span are similar to Olli barley in their response to lime.

D. Prediction of Soil Acidity Damage to Crops

The following soil criteria: soluble Al, soluble Mn, exchangeable Al, percentage base saturation, pH in water, and pH in KCl, were used in correlation analyses with percent yield of five crops grown on unlimed and limed soils in the field. (Percent yield is the yield on no lime treatments as a percentage of the yield of limed treatments.)

On assessing the correlation coefficients obtained and the correlation of the soil criteria with one another (Appendix V and VI), a multiple correlation and regression analysis was employed to determine if more than one soil factor would provide a better prediction of crop response to lime. The percent yield data used in the correlation analyses are given in Appendix VII.

Soil Criteria for Predicting Crop Response to Lime

The results of the correlation analyses are given in Appendix V and summarized in Table 10. Soil Al (soluble or exchangeable) gave the highest correlations with percent yields of barley, rape, red clover, and alfalfa when nitrogen was applied (alfalfa +N). For alfalfa without applied nitrogen (alfalfa -N), soil pH gave the highest correlation with percent yield. As shown in Appendix VI, percentage base saturation was highly correlated with soluble and exchangeable Al ($r = -0.92$ and -0.97 , respectively) and therefore gave similar results to soluble and exchangeable Al when correlated with percent yield of the crops. Percent base saturation gave slightly lower correlation than soluble or exchangeable Al with percent yield of barley, rape and red clover and gave substantially lower correlation than pH with percent yield of alfalfa (-N) (Table 10). In addition, the determination of percentage base saturation is not as convenient as pH and Al for routine laboratory analyses since percentage base saturation requires the determination of all exchangeable cations.

Although soluble and exchangeable Al gave equally high correlation coefficients with percent yield of the various crops,

Table 10. Summary of Correlations of Percent Yield with Soil Criteria

% Yield vs. Soil Criteria									
Crop	No. of Sites	Soluble Al	Soluble Mn	Exchangeable Al	% Base Saturation	pH Water	pH KCl		
								---	---
Both Areas Minus Innisfail South									
Alfalfa (-N) 2 cuts	22	-0.72 ¹	-0.06	-0.71 ²	0.56	0.73	0.71		
Alfalfa (+N) 2 cuts	22	-0.66	-0.06	-0.67	0.62	0.57	0.48		
Clover (-N)	20	-0.88	-0.22	-0.88	0.82	0.73	0.38		
Clover (+N)	20	-0.91	0.03	-0.89	0.82	0.54	0.17		
Olli Barley	21	-0.89	-0.03	-0.87	0.81	0.71	0.46		
Galt Barley	21	-0.91	-0.01	-0.93	0.91	0.73	0.53		
Span Rape (Seed)	22	-0.47	-0.28	-0.42	0.36	0.45	0.25		
Span Rape (Straw)	22	-0.82	-0.04	-0.81	0.78	0.72	0.52		
Both Areas Minus 5 Sites in East Central Alberta and Innisfail Sites									
Alfalfa (-N) 2 cuts	19	-0.78 ¹	-0.15	-0.78 ²	0.56	0.82	0.80		
Alfalfa (+N) 2 cuts	18	-0.66	-0.02	-0.66	0.64	0.67	0.55		
Clover (-N)	18	-0.90	-0.17	-0.89	0.83	0.73	0.37		
Clover (+N)	18	-0.91	0.002	-0.89	0.83	0.59	0.20		
Olli Barley	15	-0.90	0.02	-0.89	0.83	0.73	0.45		
Galt Barley	15	-0.93	-0.02	-0.95	0.92	0.79	0.54		
Span Rape (Seed)	18	-0.58	0.008	-0.55	0.48	0.41	0.23		
Span Rape (Straw)	18	-0.89	0.24	-0.90	0.86	0.76	0.56		

Table 10. (Continued)

Crop	No. of Sites	% Yield vs. Soil Criteria					
		Soluble Al	Soluble Mn	Exchangeable Al	% Base Saturation	pH Water	pH KCl
--- Correlation Coefficients ---							
<u>Peace River Area</u>							
Alfalfa (-N) 2 cuts	12	-0.77 ¹	-0.18	-0.75 ²	0.60	0.76	0.76
Alfalfa (+N) 2 cuts	12	-0.67	-0.01	-0.67	0.64	0.65	0.49
Clover (-N)	13	-0.93	-0.20	-0.92	0.84	0.84	0.39
Clover (+N)	13	-0.94	0.002	-0.92	0.85	0.68	0.23
Olli Barley	10	-0.98	0.11	-0.96	0.89	0.67	0.24
Galt Barley	10	-0.95	0.02	-0.96	0.92	0.76	0.40
Span Rape (Seed)	12	-0.68	0.51	-0.66	0.60	0.43	0.20
Span Rape (Straw)	12	-0.91	0.53	-0.93	0.90	0.78	0.59

¹ Log of soluble Al.

² Log of exchangeable Al.

soluble Al showed some advantages over exchangeable Al. On two soils that contained high levels of Al (Silver Valley and Innisfail South sites), soluble Al provided a better index of Al toxicity than exchangeable Al. The soil from the Silver Valley site contained 45 and 670 ppm of soluble and exchangeable Al, respectively, and the Innisfail South soil contained 152 and 620 ppm of soluble and exchangeable Al, respectively (Appendix III). There was no crop growth on the unlimed soil at the Innisfail site (152 ppm of soluble Al) but some yield of barley and rape was obtained at the Silver Valley site (45 ppm of soluble Al). Soluble Al reflected the difference in crop growth obtained on these strongly acid soils while exchangeable Al did not. In addition, Mn measured in the 0.02M CaCl_2 extraction used for soluble Al has been shown to be a good criteria for predicting Mn toxicity to rape (Hoyt and Nyborg, 1972). The simultaneous extraction of Al and Mn is an advantage for routine laboratory analyses. Because of the advantages of soluble Al over exchangeable Al outlined, only soluble Al was used in the multiple correlation and regression analyses.

Since alfalfa is normally grown with little or no applied nitrogen, soil pH provides the best prediction of crop response to lime. For alfalfa (-N) pH in KCl was equally as good as pH in water but for all other crops, pH in water gave substantially higher correlations than pH in KCl. The log of soluble Al was as highly correlated with percent yield of alfalfa (-N) as pH, but the relationship between soluble Al and percent yield is not as useful as pH and percent yield because alfalfa yields are reduced substantially by acidity in the pH range 5.5 to 6.0, which is above the range where

Al toxicity occurs.

Using only one soil criteria at a time, soluble Al provided the best prediction of crop response to lime for barley, rape, red clover and alfalfa (+N). For alfalfa (-N), pH provided the most useful prediction of lime response. The relationships between the most useful soil criteria and percent yield of the various crops are illustrated in the scatter diagrams (Figures 2, 3, 4 and 5).

The Effect of Soil Type and Region

The yield data were divided into three sub-groupings to determine if soil type or region was affecting the correlations (Table 10). Data from the Innisfail South site was not included in the correlation analyses. This site had received elemental sulphur from a nearby gas processing plant and was extremely acid. Preliminary analyses showed that the extreme acidity and very high Al levels in this soil tended to bias the data and cause unusually high correlation coefficients.

The first group of correlations (Table 10) includes data from all sites at which reliable yields were obtained, except the Innisfail South site. In the second group of data, five sites from East Central Alberta, namely: Raessler, Bertsch, Hepp, Lyster and Kay, were omitted. The above sites were in a drier region and only the surface (0 - 6") was acid. The correlations, particularly for alfalfa, improved when those five sites were omitted (Table 10). Crop response to lime tended to be lower on the five sites than on most other sites at comparable pH and Al levels. The somewhat different response pattern of alfalfa

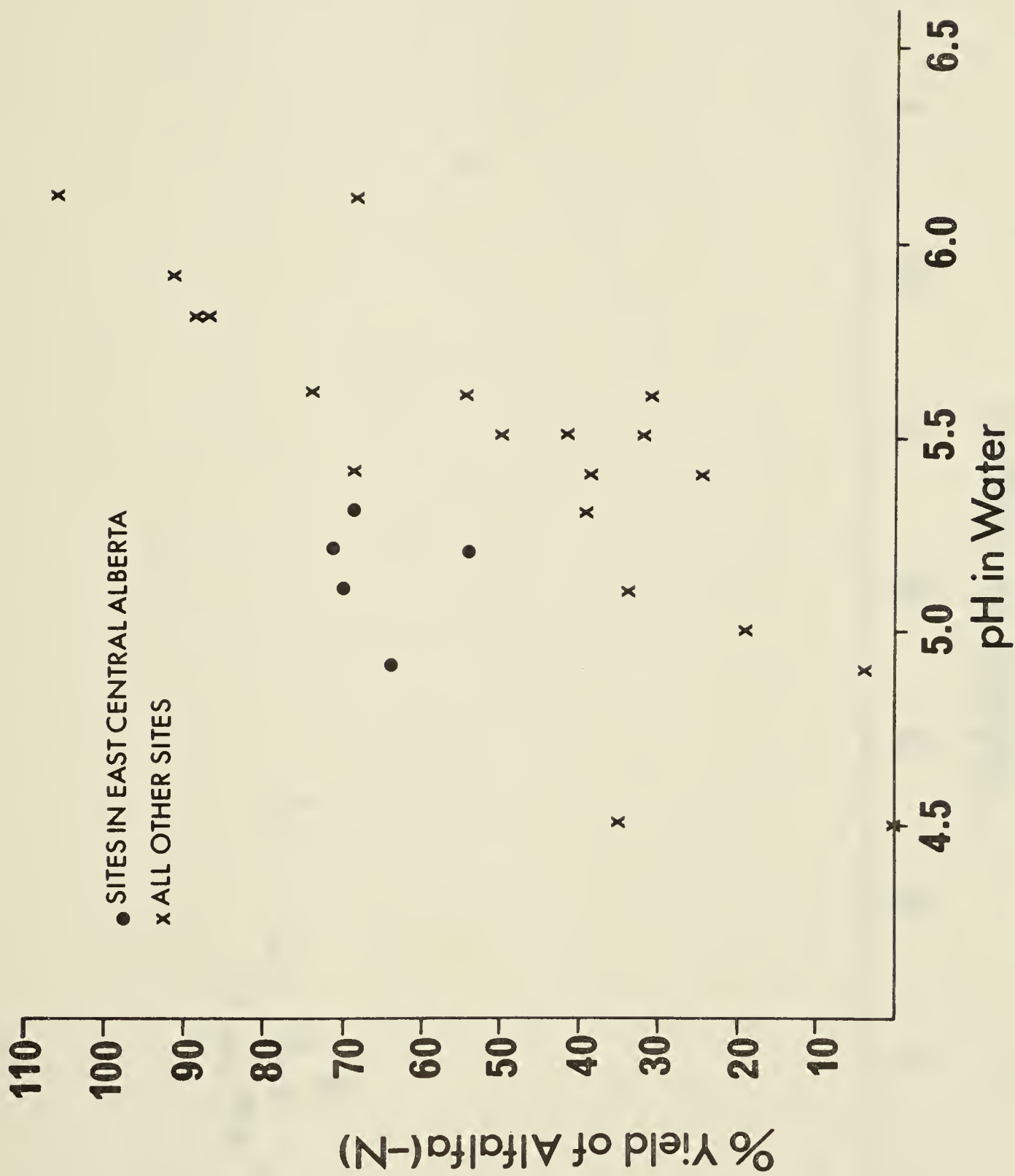


Figure 2. Percent yield of alfalfa (-N) versus soil pH in water.

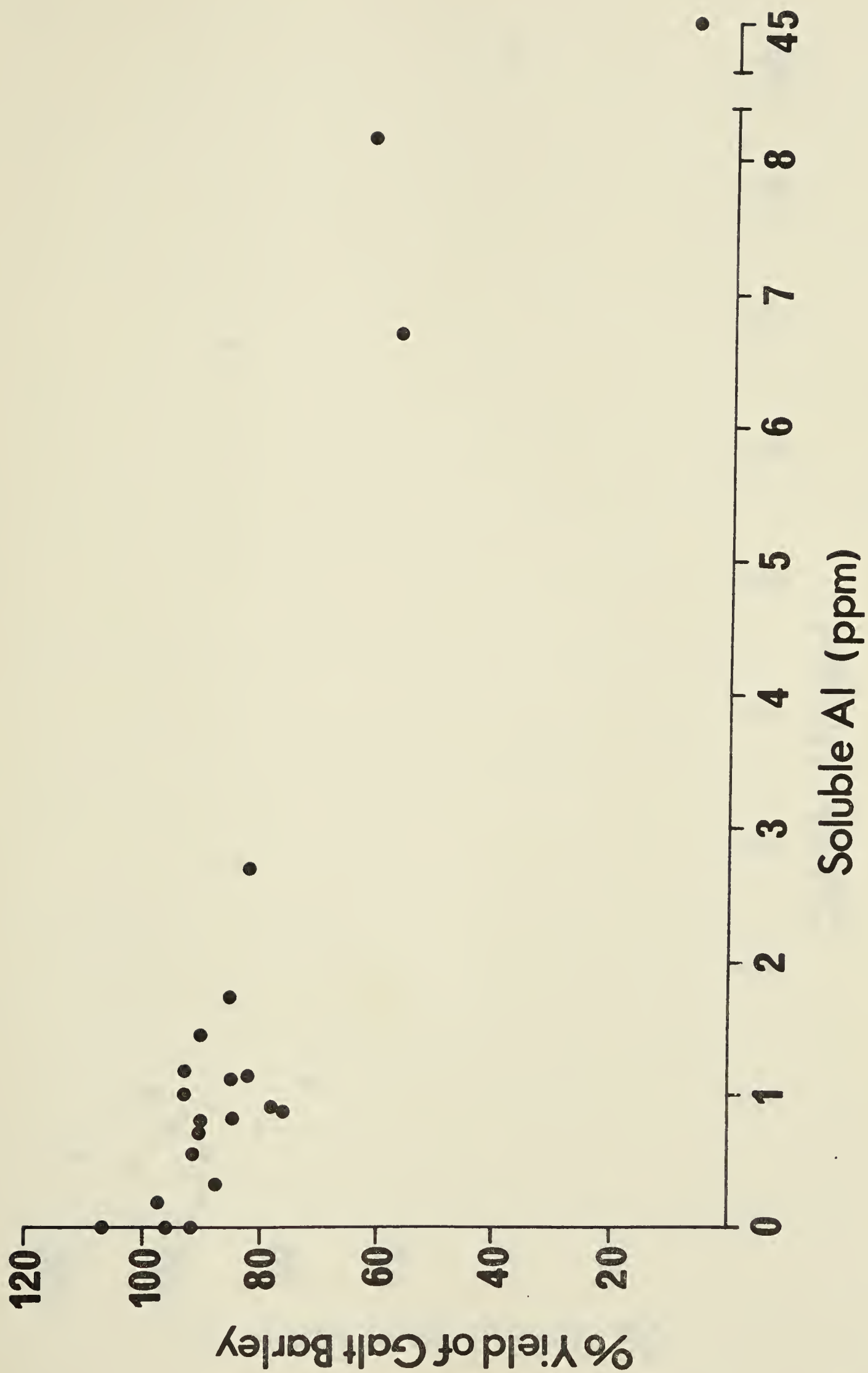


Figure 3. Percent yield of Galt barley versus soluble Al.

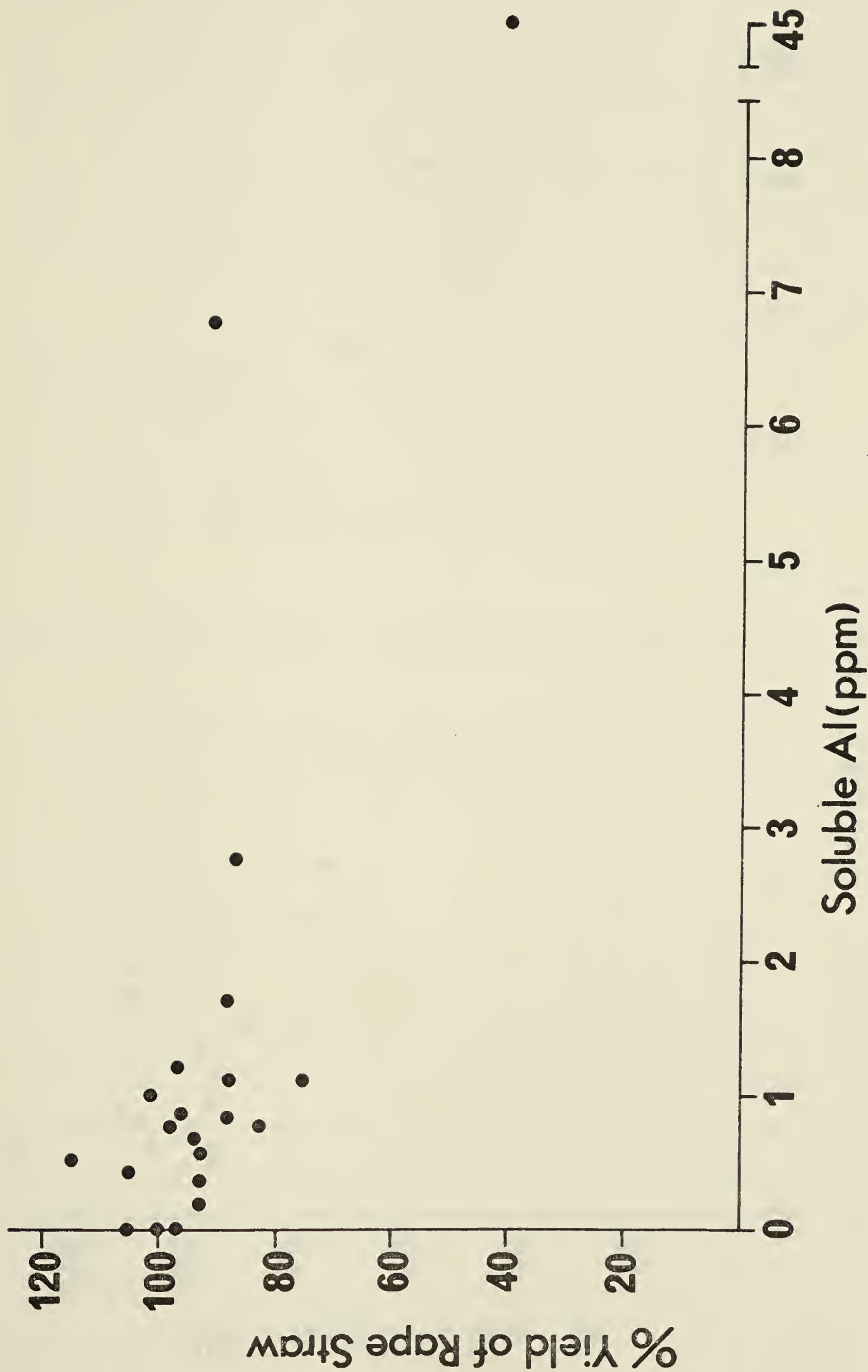
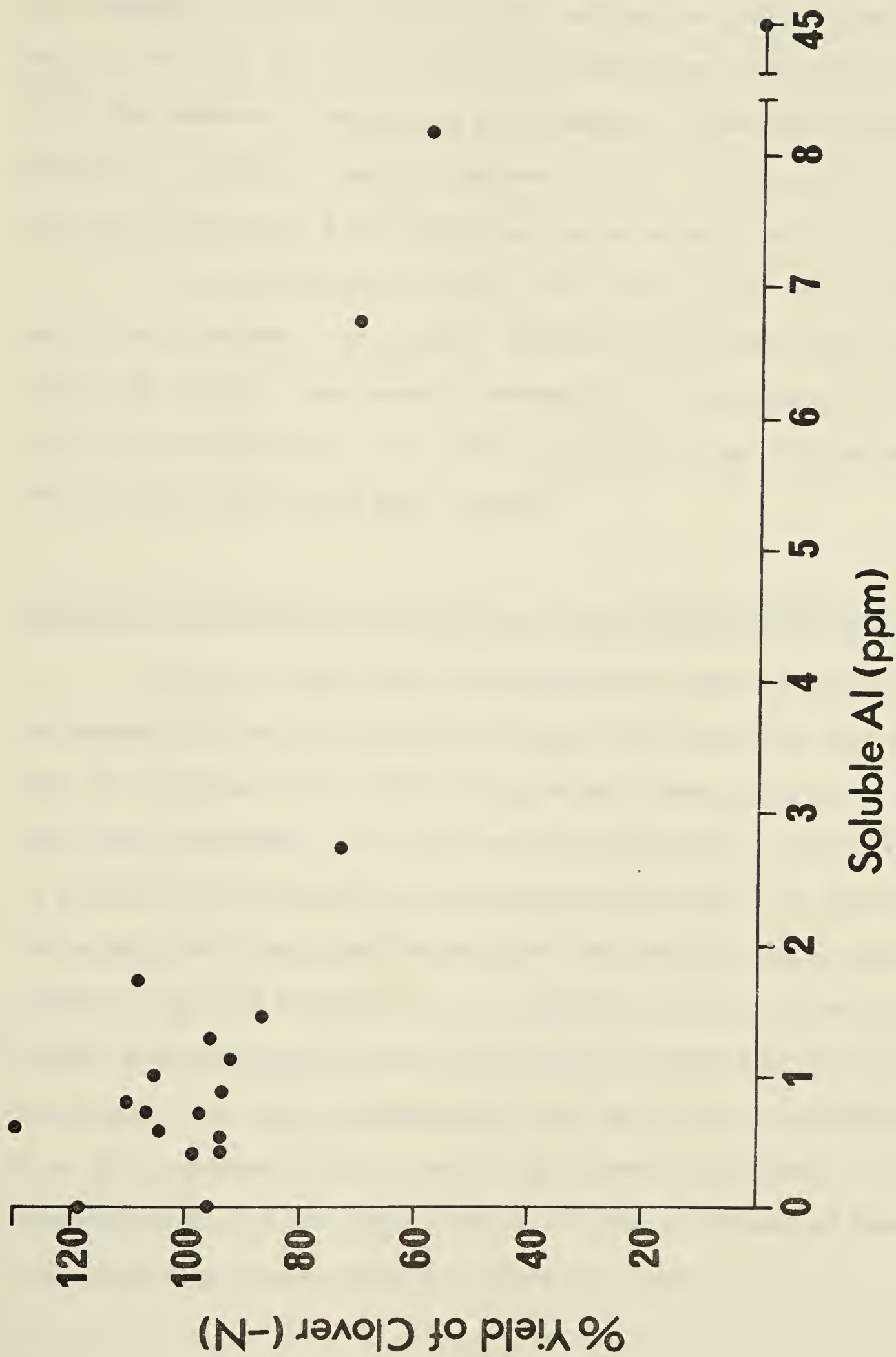


Figure 4. Percent yield of rape straw versus soluble Al.



obtained on the five sites is illustrated in Figure 2, and the following are suggested as reasons for the lower response to lime: (i) the shallow depth of acidity, (ii) drier condition restricting yield potential, and (iii) the presence of relatively high levels of soluble Mn which are reported to reduce Al toxicity (Jackson, 1967). In the case of alfalfa, nitrogen fixation may have taken place below the acid surface horizon.

In the third group of data, only sites in the Peace River region were included. The results obtained for the Peace River region (Table 10) indicate that there is essentially no difference in the correlation obtained for this region compared to those obtained when results from both regions were included.

Linearity of the Relationship Between Percent Yield and Soil Criteria

$\log_{10}$ and square root transformation of the soluble Al, exchangeable Al, soluble Mn and percentage base saturation data were made to determine if the relationship between these criteria and percent yield was curvilinear. For rape, barley and red clover, the correlations of soluble and exchangeable Al with percent yield were not improved with the square root transformation and were lower when the $\log_{10}$ transformation was used (Appendix V). For alfalfa the correlation with soluble and exchangeable Al was substantially improved by the transformations. The $\log_{10}$ transformation gave the highest correlation ($r = -0.72$ compared to $r = -0.49$ for the linear relationship). The transformations did not improve the correlation of percentage base saturation with percent yield for any of the crops.

Multiple Correlation and Regression Analyses

Multiple regression analyses were used to relate percent yield of the various crops to the following soil criteria: soluble Mn, soluble Al, percentage base saturation and pH in water (Appendix VIII). Soluble Mn was used in conjunction with each of the other soil criteria to determine if its inclusion in the regression would improve the correlation with percent yield. As shown in Appendix VI, soluble Mn was poorly correlated with soluble Al ($r = 0.11$) and percent base saturation ($r = 0.14$) but showed some relationship to pH ($r = -0.57$). Since soluble Mn was not correlated with soluble Al or percentage base saturation, it was used as an additional independent variable with both soluble Al and percentage base saturation in regression analyses. Soluble Mn was also used with pH in regression analyses but the autocorrelation between soluble Mn and pH ($r = -0.57$) make their use as independent variables somewhat questionable.

As shown in Table 10, soluble Mn was not related to percent yield of any of the crops except to a limited extent with clover (-N) and rapeseed ($r = -0.22$ and -0.28 , respectively). When only the data from the Peace River area was included, soluble Mn was positively correlated with percent yield of rape (seed and straw). This appears to be an anomaly in the data as a result of the somewhat erratic yields that occurred at the Dyck and Derksen sites where soluble Mn levels were relatively high. Soluble Mn levels were relatively low at all other sites in the Peace River region.

As shown in the summary of multiple regression analyses (Table 11), the use of soluble Mn with soluble Al improved the correlation

Table 11. Simple and Multiple Correlation Coefficients of Soluble Al, pH and Soluble Mn with Percent Yield

Crop	No. of Sites	Soluble Al or pH (r)	Soluble Al or pH plus Soluble Mn (R)
-- Correlation Coefficients --			
<u>Both Areas Minus Innisfail South</u>			
Alfalfa (-N)	22	0.73** ²	0.82**
Clover (-N)	20	-0.92** ¹	0.93**
Olli Barley	21	-0.90** ¹	0.90**
Galt Barley	21	-0.96** ¹	0.96**
Span Rape (Seed)	22	-0.47* ¹	0.63**
Span Rape (Straw)	22	-0.82** ¹	0.86**

* and ** indicates significance at the 5% and 1% levels, respectively.

¹ Indicates soluble Al.

² Indicates pH.

only for rape (seed and straw). For barley and red clover, the correlation with soluble Al was already high (i.e.: $r = -0.91$ and -0.88 , respectively) and little improvement would be expected (Table 10). In the case of rape seed, the standard partial regression coefficients, which indicate the relative importance of the independent variables in the regression were -0.59^{**} and -0.44^{*} for soluble Al and soluble Mn, respectively; and -0.89^{**} and -0.29^{*} , respectively for rape straw.

* and ** indicates significance at the 5% and 1% levels, respectively.

Soluble Mn appears relatively more important in the case of rape seed than in the case of rape straw. However, as shown in Table 10, the correlation with soluble Al alone was higher for rape straw ($r = -0.82$) than for rape seed ($r = -0.47$). Soluble Mn and pH in the regression increased the correlation obtained for alfalfa (-N) (Table 11). Although pH and soluble Mn are auto-correlated ($r = -0.57$), the standard partial regression coefficient for Mn is significant, indicating that soluble Mn may be a useful criteria, when used in conjunction with pH, for predicting response of alfalfa to lime.

In summary, the results of the correlation and regression analyses show that soluble Al alone provided the best prediction of crop response to lime for barley and red clover. For rape, the prediction of lime response was significantly increased when soluble Mn was used in addition to soluble Al in regression analyses. The results reported here concur with results obtained by Hoyt and Nyborg (1972). In a greenhouse experiment using 40 soils, barley and alfalfa response to lime was found to be related only to soluble Al, whereas rape response was related to both soluble Al and soluble Mn. Percentage base saturation was fairly well correlated with percent yield of all the crops grown in the study reported here but it gave slightly lower correlation coefficients than soluble Al for barley and red clover. For alfalfa, pH gave higher correlation coefficients than percentage base saturation. The determination of percentage base saturation is also a less desirable measurement for routine laboratory analyses since it involves the determination of several cations and is therefore more time consuming. In this study the most useful soil criteria for predicting crop response

to lime were pH, soluble Al and soluble Mn. The simultaneous extraction of Al and Mn with 0.02M CaCl_2 provides an additional convenience for routine laboratory analyses.

Nodulation Assessment

The assessment of nodules on the alfalfa and clover roots provided a semi-quantitative method of determining effective nodulation. The detailed results of the nodulation assessment are given in Appendix IX and are summarized by crop and treatment in Table 12. The relationship between change in nodulation score from liming, percent yield and soil pH are illustrated in Figures 6, 7, 8 and 9.

Comparing lime and no lime for alfalfa (-N) in Table 12, it is evident that lime substantially increased nodule score at most sites. Only at the Cooking Lake (pH 6.1), Hastings (pH 5.8), Bessborough (pH 5.6) and Buick Creek (pH 5.6) sites were the nodulation scores not increased by liming. Below pH 5.6, there is a marked tendency for the nodulation score of alfalfa to be reduced (Figure 6). Of the factors assessed (color: i.e. percentage of pink nodules; number; size; and position), the percentage of pink nodules was the one most frequently reduced by acidity. Jackson (1967) indicates that symbiotic nitrogen fixation can be separated into three processes; namely (i) microbial growth and survival, (ii) nodulation (the infection process), and (iii) nitrogen fixation which involves the function of the organisms in the host plant; and that soil acidity can affect all three of these processes. The frequent reduction in the percentage of pink nodules on the unlimed soils indicates that nitrogen fixation may be the most

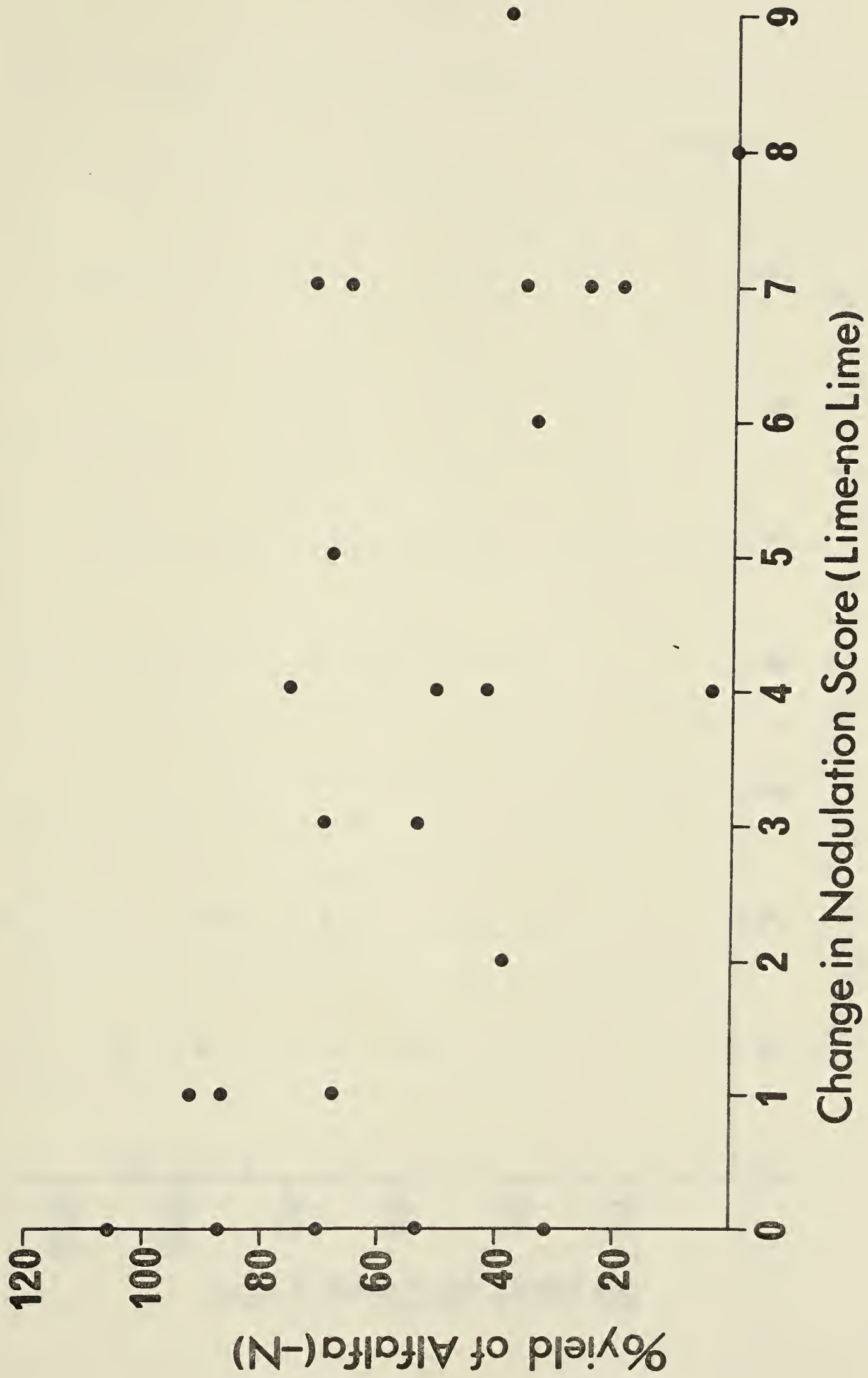


Figure 8. Percent yield of alfalfa (-N) versus change in nodulation score.

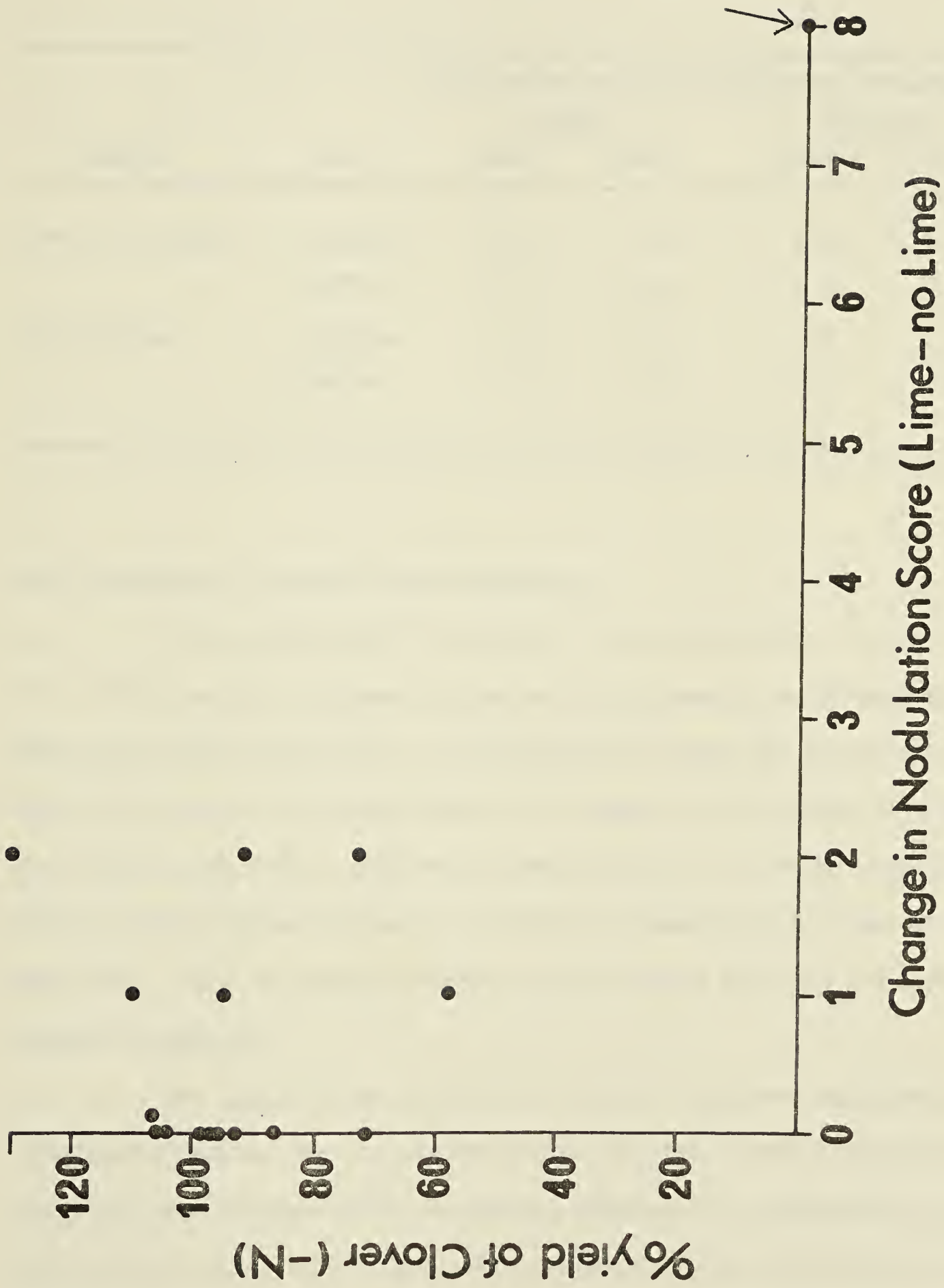


Figure 9. Percent yield of clover (-N) versus change in nodulation score.

Table 12. The Effect of Lime and Nitrogen on Nodulation Scores of Alfalfa and Red Clover in 24 Field Experiments

Region	Crop	Nodulation Score of Different Treatments			
		Lime		No Lime	
		(+N)	(-N)	(+N)	(-N)
Central Alberta	Alfalfa	4.6	7.6	2.6	4.4
	Clover	4.1	6.8	4.3	5.8
Peace River	Alfalfa	7.2	8.2	3.8	4.4
	Clover	7.0	7.1	6.3	6.6

acid sensitive of these three processes.

Soil acidity had less effect on the nodulation scores obtained for clover and the increase in the score obtained from liming was less than for alfalfa (Table 12). Nodulation of clover was severely restricted only at the Silver Valley site (pH 4.5). The Dyck site was also pH 4.5 but had a relatively high score of 7. However, the Silver Valley soil contains 45 ppm of soluble Al compared to 8.2 ppm in the Dyck soil. The 34 ppm of soluble Mn in the Dyck soil did not severely reduce nodulation.

The application of 100 lb./acre of fertilizer nitrogen substantially reduced the nodulation scores of alfalfa and clover on both the limed and unlimed soils in Central Alberta, but caused only a small reduction on sites in the Peace River region. The percentage of pink nodules was decreased on nitrogen treatments in Central Alberta, but

this trend is not evident in the data from the Peace River region. The time of nitrogen application is the only apparent reason for the difference that occurred between the two regions. Nitrogen was applied in late fall (October) in the Peace River region and in spring (May) in Central Alberta.

Change in nodulation score was used in correlation analyses with percent yield to determine if it was useful for predicting crop response to lime. The correlation coefficients obtained for alfalfa (-N) and clover (-N) were -0.54 and -0.73, respectively. Although some relationship between percentage yield and nodulation score is indicated, the prediction was not as good as pH for alfalfa or soluble Al for clover. As illustrated in Figure 9, the correlation coefficient obtained between percent yield of clover and change in nodule score is very dependent on one point.

From the summary of nodulation scores (Table 12) and the effect of soil pH on nodule score illustrated in Figure 6, it is evident that soil acidity restricts effective nodulation of alfalfa. Soil acidity had less effect on nodulation of clover. Nodulation of clover was severely restricted at one site which contained a very high level of soluble Al (45 ppm). The results of the nodulation assessment generally concur with the yield responses obtained. The semi-quantitative nature of the nodule assessment and the small number of plants assessed may have limited the accuracy of determining effective nodulation. Also, factors other than acidity such as the level of available soil nitrogen can affect nodule score (Fred et al., 1932).

SUMMARY AND CONCLUSIONS

There are approximately 28 million acres of cultivated land in Alberta of which 20.6% are $\text{pH} \leq 6.0$, 3.9% are $\text{pH} \leq 5.5$ and 0.4% are $\text{pH} \leq 5.0$ (from the summary of soil pH in Alberta by the Alberta Soil and Feed Testing Laboratory, as referred to in the Introduction). The application of lime resulted in yield increases of alfalfa on all soils of $\text{pH} \leq 6.0$, indicating that alfalfa production would be reduced by acidity on about 5 million acres. Yield increases of barley and rapeseed occurred at $\text{pH} \leq 5.5$ indicating soil acidity would reduce yields of these crops on one-half to one million acres. Yields of all the crops grown were severely reduced on soils of $\text{pH} \leq 5.0$ indicating that there are about 100,000 acres of very strongly acid soils on which yields of many crops would be severely restricted.

Alfalfa was the least acid tolerant of the crops grown and its response to lime was best predicted by soil pH (Table 10). The results of the greenhouse experiment showed no difference in acidity tolerance among the four alfalfa varieties grown (Table 3). Therefore, the results obtained in the field experiments using Ladak alfalfa appear applicable to several commonly grown varieties.

Differences in acidity tolerance of barley varieties are evident in the results of the greenhouse and field experiments. The varieties Olli and Galt grown in the field experiments represent the range in acidity tolerance found among commonly grown varieties in the region studied. The results of Foy et al. (1965) indicate that a much wider range in acidity tolerance of barley varieties exists than was obtained

in this study. Hewitt (1948), Foy (1965), Hoyt and Nyborg (1972) and others have established that barley is more sensitive to Al toxicity than to Mn toxicity. The results reported here show that measurement of soil Al provides the best prediction of lime response for barley.

The acidity tolerance of rape was shown to be similar to Olli barley in both the greenhouse and field experiments. Lodging and seed shattering caused the yield response of rapeseed to lime to be more erratic than for the other crops and as a result, correlation coefficients obtained for rapeseed are lower than those obtained for the other crops (Table 10). The use of both soluble Al and soluble Mn as independent variables in regression analyses significantly improved the correlation over that obtained using soluble Al alone.

Red clover was the most acid tolerant crop grown in the study. Significant lime responses were not obtained above pH 5.0. Soluble Al gave the best prediction of red clover response to lime. On sites in East Central Alberta, red clover was difficult to establish and yielded poorly, possibly due to its lack of drought tolerance. On acid soils in all other regions of the study, the substantially greater acidity tolerance of red clover made it a useful alternative to liming, to permit alfalfa production. However, the yield potential of red clover appears to be somewhat lower than alfalfa (Table 8).

Of the soil criteria studied, soluble Al and Mn extracted with 0.02M CaCl_2 , and pH were the most useful for predicting crop response to lime. The relatively rapid and simultaneous extraction of Al and Mn with dilute CaCl_2 as developed by Hoyt and Nyborg (1971) provides a method of predicting Al and Mn toxicity to crops that is useful for

routine soil analyses. The determination of pH, soluble Al and soluble Mn provides a more complete assessment of soil acidity factors than pH alone.

The nodulation assessment of alfalfa and red clover indicated that effective nodulation of alfalfa was restricted below pH 5.6, but there was little apparent effect on red clover nodulation, except on one site which had a very high level of soluble Al (45 ppm). The correlations obtained between "change in nodulation score as a result of lime application" and percent yield of alfalfa and red clover were not as high as those obtained with pH and soluble Al.

Based on the results of this study and supporting evidence in the literature, a number of conclusions can be made as to the extent, cause, and method of predicting soil acidity damage to several crops grown in the region studied.

1. Alfalfa yields are reduced on acid soils of pH ≤ 6.0 . The application of lime resulted in very large increases in yields of alfalfa, and soil pH provided the most useful prediction of lime response.
2. Red clover was much more tolerant to acidity than alfalfa. The application of lime resulted in significant yield increases only on soils of pH ≤ 5.0 . Soluble Al gave the best prediction of lime response.
3. Barley responded to lime on soils of pH ≤ 5.5 . Some differences in tolerance to acidity were shown among barley varieties. Soluble Al gave the best prediction of lime response.

4. In both greenhouse and field experiments, response of rapeseed to lime was similar to Olli barley. Soluble Al and soluble Mn used together gave a better prediction of response to lime than soluble Al alone.
5. The relatively rapid extraction procedure for Al and Mn using dilute CaCl_2 , developed by Hoyt and Nyborg (1971), used in conjunction with soil pH provided an accurate means of predicting response to lime of several crops on a wide range of acid soils. This was the first time that a method of determining Al and Mn, suitable for routine analyses, has been found effective in predicting crop response to lime under field conditions.

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APPENDIX I

Classification and Legal Location of Soils at 28 Sites Used for Field Experiments

Site Name	Subgroup	Series	Legal Location
Raessler	Dark Brown Solod	Not named	NE 8-31-17-4
Bertsch	Dark Brown Solod - Eluviated Dark Brown (complex)	Not named	SE 25-32-17-4
Hepp	Dark Brown Solonetz	Not named	NW 36-38-14-4
Lyster	Black Solod	Daysland	NW 21-39-18-4
Kay	Solodic Black	Not named	NW 28-39-18-4
Innisfail North	Orthic Black	Penhold	SW 1-35- 1-5
Innisfail South	Orthic Black	Penhold	SW 1-35- 1-5
Cormie	Gray Solod	Lowater	SW 14-52- 5-5
Horen	Solodic Gray Luvisol	Nakamun	SW 18-52- 5-5
Weist	Dark Gray Luvisol	Macola	NW 32-53- 7-5
Webster	Orthic Gray Luvisol	Breton	SW 6-48- 3-5
Lowie	Solodic Dark Gray	Majeau	NE 35-56- 4-5
Cooking Lake	Dark Gray Luvisol	Uncas	NW 15-51-21-4
Williams	Orthic Gray Luvisol	Not named	NE 15-59-14-4
Valleyview North	Dark Gray Solonetz	Valleyview	SE 26-70-22-5
Valleyview South	Gray Solod	Donnelly	SW 29-69-22-5
Derksen	Orthic Gleysol	Not named	SW 34-104-14-5
Dyck	Rego Gleysol	Savage	NE 35-104-14-5
Wanham	Solodic Black	Rycroft	SW 35-77- 3-6

Appendix I. (Continued)

Site Name	Subgroup	Series	Legal Location
Spirit River	Gray Solod	Donnelly	NW 24-78- 8-6
Silver Valley	Humic Eluviated Gleysol	Josephine	SE 15-82-10-6
Fourth Creek	Humic Eluviated Gleysol	Josephine	SW 28-81- 9-6
Wembley	Gray Solod	Donnelly	SE 34-70- 8-6
Border	Gray Solod	Hazelmere	SE 7-75-13-6
Bessborough	Gray Solod	Alcan	SE 1-79-17-6
Prespatou	Gray Solod	Alcan	(Not established
Hastings	Gray Solod	Alcan	-- a different
Buick Creek	Low Humic Eluviated Gleysol	Buick	land survey sys- tem in N. E. British Columbia)

APPENDIX II

Soil pH (H₂O) to Depth for 28 Sites Used

for Field Experiments

Site	pH of Different Depths (inches)				
	0 - 6	6 - 12	12 - 24	24 - 36	36 - 48
<u>Central Alberta</u>					
Raessler	5.14	6.42	8.58	8.45	--
Bertsch	6.04	6.90	7.90	8.05	--
Hepp	5.56	6.68	8.18	8.33	--
Lyster	5.32	6.53	7.61	8.23	--
Kay	5.50	6.09	7.61	8.69	--
Innisfail North	5.67	6.82	6.94	7.80	--
Innisfail South	3.62	6.20	6.50	7.94	--
Cormie	5.32	5.28	5.73	7.42	--
Horen	5.41	5.28	5.73	7.42	--
Weist	5.41	4.84	4.98	7.46	--
Webster	5.61	5.36	5.50	5.93	--
Lowie	5.54	6.04	8.03	7.80	--
Cooking Lake	6.22	6.68	6.79	7.98	--
Williams	6.14	5.92	5.64	7.15	--
<u>Peace River</u>					
Valleyview North	5.37	7.10	8.36	8.04	7.64
Valleyview South	5.52	5.25	5.85	8.22	8.00
Derksen	5.06	4.64	4.18	4.08	4.23
Dyck	4.33	3.85	3.76	3.86	4.81
Wanham	5.54	6.50	7.91	7.78	7.70
Spirit River	5.40	5.46	7.79	8.10	7.98
Silver Valley	4.40	4.05	3.77	3.68	3.52

Appendix II. (Continued)

Site	pH of Different Depths (inches)				
	0 - 6	6 - 12	12 - 24	24 - 36	36 - 48
<u>Peace River</u>					
Fourth Creek	4.90	4.50	4.18	4.06	4.07
Wembley	6.10	6.02	7.86	8.40	8.20
Border	5.37	5.40	5.83	8.01	7.86
Bessborough	5.68	5.00	4.68	4.70	4.70
Prespatou	4.72	5.11	5.54	7.24	7.60
Hastings	5.67	4.99	5.22	7.64	7.63
Buick Creek	5.51	5.50	5.73	7.84	8.01

pH values are averages of duplicate determinations.

Variation between duplicate determinations ranges from 0.0 to 0.1.

APPENDIX III

Soil Analyses Data for 28 Field Sites

Region and Site	0.02M CaCl ₂ Extraction ²			1N KCl Extraction				NH ₄ OAc Extraction					pH		Lime Requirement to pH 6.5 Ca(OH) ₂ (cwt/acre)
	Sol.Al (ppm)	Sol.Mn (ppm)	Ex.Al (ppm)	Ca (m e q / 1 0 0 g)	Mg (m e q / 1 0 0 g)	Na (m e q / 1 0 0 g)	% Base Sat.	Ca (--- m e q / 1 0 0 g ---)	Mg	Na	K	% Base Sat.	pH		
													Water	KCl	
Central Alberta															
Raessler	2.7	24	81	6.2	2.8	0.35	88	8.2	3.1	0.43	1.10	52	4.9	3.8	59.8
Bertsch	1.2	12	18	4.1	1.6	0.24	93	4.5	1.6	0.17	0.66	52	5.2	4.1	24.4
Hepp	1.1	16	9	5.5	2.4	0.52	93	--	--	--	--	--	5.2	4.2	45.0
Lyster	0.9	21	8	6.9	2.6	0.56	94	--	--	--	--	--	5.1	4.2	62.6
Kay	0.8	12	1	8.5	3.4	0.22	98	--	--	--	--	--	5.3	4.3	38.8
Innisfail North	0.2	10	0	18.1	2.2	0.20	99	--	--	--	--	--	5.4	4.6	38.8
Innisfail South	152.0	132	620	8.9	1.2	0.17	59	--	--	--	--	--	3.4	3.1	112.0
Cormie	1.1	12	53	8.8	2.4	0.52	91	10.5	2.7	0.52	0.37	68	5.1	3.9	32.6
Horen	0.6	8	9	8.8	2.5	0.22	97	--	--	--	--	--	5.3	4.2	28.0
Lowie	0.3	8	8	20.2	7.9	1.17	96	--	--	--	--	--	5.8	4.3	58.6
Weist	0.3	10	8	17.9	6.7	0.26	99	--	--	--	--	--	5.5	4.3	41.2
Webster	0.7	13	9	6.2	1.0	0.20	96	--	--	--	--	--	5.6	4.4	20.0
Cooking Lake	0.0	7	1	6.9	1.6	0.20	98	--	--	--	--	--	6.1	5.2	10.0
Williams	0.0	6	1	5.1	0.8	0.17	97	6.2	0.82	0.11	0.17	97	6.0	5.0	8.6
Peace River															
Valleyview North	1.7	8	105	4.8	3.6	2.02	81	--	--	--	--	--	5.4	3.8	100.0
Valleyview South	0.9	8	18	7.1	2.4	0.35	95	--	--	--	--	--	5.5	4.2	60.0
Derksen	1.4	17	12	12.3	6.1	0.30	98	--	--	--	--	--	5.0	4.2	85.0
Dyck	8.2	34	137	15.2	5.9	0.65	91	17.5	6.8	0.74	1.10	59	4.5	3.7	170.0
Wanham	0.7	6	18	10.6	5.7	1.04	93	--	--	--	--	--	5.4	4.1	60.0
Spirit River	1.0	5	33	6.0	2.9	0.50	91	--	--	--	--	--	5.4	4.1	55.0
Silver Valley	45.0	2	670	4.4	0.9	0.24	41	4.8	1.0	0.17	0.82	19	4.5	3.7	160.0
Fourth Creek	6.5	5	142	6.9	2.4	0.22	84	--	--	--	--	--	4.9	3.9	104.0
Wembley	0.0	3	2	11.2	4.0	0.26	98	--	--	--	--	--	5.9	4.9	20.0
Border	0.8	5	20	5.8	1.8	0.22	94	--	--	--	--	--	5.5	4.2	30.0
Bessborough	0.5	7	5	6.0	1.2	0.17	97	--	--	--	--	--	5.6	4.6	40.0
Prespatou	6.8	7	176	5.0	1.4	0.22	75	--	--	--	--	--	4.9	3.7	110.0
Hastings	0.4	5	4	12.5	4.5	0.20	99	--	--	--	--	--	5.8	4.6	80.0
Buick Creek	0.6	4	14	13.7	7.2	0.35	98	--	--	--	--	--	5.6	4.4	110.0

APPENDIX IV

Seasonal Variation in Soil pH (0-6") at 28 Field Sites

Site	Treatment	pH				
		Spring 1970	Summer 1970	Fall 1970	Spring 1971	Fall 1971
Raessler	No Lime	5.1	5.0	4.8	4.9	4.9
	Lime	--	6.4	6.4	6.0	6.0
Bertsch	No Lime	6.0	5.3	5.2	5.2	5.1
	Lime	--	6.2	6.2	6.4	6.1
Hepp	No Lime	5.6	5.3	5.1	5.2	5.1
	Lime	--	6.2	6.2	6.1	6.1
Lyster	No Lime	5.3	5.3	5.0	5.1	5.1
	Lime	--	6.2	6.7	6.4	6.5
Kay	No Lime	5.5	5.3	5.2	5.3	5.2
	Lime	--	6.3	--	6.1	6.4
Innisfail North	No Lime	--	--	5.7	5.5	5.4
	Lime	--	--	--	6.7	6.4
Innisfail South	No Lime	--	--	3.6	3.4	3.6
	Lime	--	--	--	6.5	5.6
Cormie	No Lime	5.3	5.1	5.0	5.1	5.1
	Lime	--	6.6	6.5	6.0	6.2
Horen	No Lime	5.4	5.2	5.2	5.3	5.1
	Lime	--	6.8	6.4	6.8	6.4
Weist	No Lime	5.4	5.5	5.5	5.6	5.5
	Lime	--	6.8	6.7	6.6	6.6
Webster	No Lime	5.6	5.5	5.5	5.4	5.4
	Lime	--	6.2	6.6	6.1	6.1
Lowie	No Lime	5.5	5.6	5.8	5.8	5.8
	Lime	--	6.5	6.4	6.6	6.8
Cooking Lake	No Lime	6.2	--	5.9	6.1	5.9
	Lime	--	--	6.5	6.6	6.3
Williams	No Lime	6.1	6.0	6.0	6.0	5.8
	Lime	--	6.5	6.6	6.6	6.2

Appendix IV. (Continued)

Site	Treatment	pH				
		Spring 1970	Summer 1970	Fall 1970	Spring 1971	Fall 1971
Valleyview North	No Lime	5.4	5.3	5.2	5.4	5.1
	Lime	--	6.4	6.6	6.5	6.6
Valleyview South	No Lime	--	5.4	5.5	5.5	5.4
	Lime	--	--	--	6.8	7.0
Derksen	No Lime	5.1	4.9	--	5.0	--
	Lime	--	6.4	--	7.1	--
Dyck	No Lime	4.3	4.3	--	4.5	--
	Lime	--	6.3	--	6.2	--
Wanham	No Lime	5.5	5.5	5.4	5.4	5.2
	Lime	--	6.6	6.4	6.3	6.7
Spirit River	No Lime	5.4	5.3	5.3	5.4	5.3
	Lime	--	6.5	6.7	6.7	6.7
Silver Valley	No Lime	4.4	4.5	4.5	4.5	4.4
	Lime	--	6.4	6.6	6.4	6.4
Fourth Creek	No Lime	4.9	--	5.0	--	4.9
	Lime	--	--	6.8	--	6.8
Wembley	No Lime	6.1	5.9	5.9	5.9	5.8
	Lime	--	6.5	6.4	6.5	6.7
Border	No Lime	5.4	5.3	5.3	5.5	5.4
	Lime	--	6.7	6.7	6.7	6.8
Bessborough	No Lime	5.7	5.7	5.7	5.6	5.6
	Lime	--	6.7	6.8	6.6	6.7
Prespatou	No Lime	4.7	4.8	4.9	4.9	4.8
	Lime	--	6.9	6.5	6.5	6.6
Hastings	No Lime	5.7	5.8	5.8	5.8	5.7
	Lime	--	7.2	6.9	6.9	7.0
Buick Creek	No Lime	5.5	5.6	5.6	5.6	5.7
	Lime	--	7.2	6.8	6.8	6.8

APPENDIX V

Correlation (r) of Percent Yield with Various Soil Criteria

Crop	No. of Sites	Log ₁₀ Transformation				Square Root Transformation				Linear				pH			
		Log ₁₀ Transformation		Square Root Transformation		Square Root Transformation		Linear		Linear		pH					
		Sol. Al ¹	Sol. Mn ¹	Ex. Al ²	Base Sat. %	Sol. Al ¹	Sol. Mn ¹	Ex. Al ²	Base Sat. %	Sol. Al ¹	Sol. Mn ¹	Ex. Al ²	Base Sat. %	H ₂ O	KCl		
Both Areas Minus Innisfail South																	
Alfalfa (-N) 1st Cut	25	-0.68	0.07	-0.69	0.51	-0.58	0.02	-0.63	0.52	-0.47	-0.02	-0.52	0.53	0.64	0.66		
Alfalfa (-N) 2 Cuts	22	-0.72	0.01	-0.71	0.54	-0.60	-0.04	-0.64	0.55	-0.49	-0.06	-0.54	0.56	0.73	0.71		
Alfalfa (+N) 1st Cut	24	-0.60	0.26	-0.53	0.64	-0.70	0.14	-0.66	0.64	-0.69	-0.002	-0.68	0.62	0.53	0.40		
Alfalfa (+N) 2 Cuts	22	-0.64	0.24	-0.59	0.64	-0.69	-0.14	-0.66	0.63	-0.66	0.06	-0.67	0.62	0.57	0.48		
Clover (-N)	20	-0.82	0.03	-0.69	0.84	-0.92	0.11	-0.87	0.83	-0.88	-0.22	-0.88	0.82	0.73	0.38		
Clover (+N)	20	-0.63	0.28	-0.49	0.86	-0.87	0.14	-0.79	0.84	-0.91	0.03	-0.89	0.82	0.54	0.17		
Olli Barley	21	-0.79	0.22	-0.65	0.84	-0.90	-0.08	-0.82	0.82	-0.89	-0.03	-0.87	0.81	0.71	0.46		
Galt Barley	21	-0.85	0.26	-0.72	0.91	-0.96	0.11	-0.92	0.91	-0.91	-0.01	-0.93	0.91	0.73	0.53		
Span Rape (Seed)	22	-0.37	-0.13	-0.12	0.40	-0.44	-0.22	-0.30	0.38	-0.47	-0.28	-0.42	0.36	0.45	0.25		
Span Rape (Straw)	22	-0.71	0.17	-0.48	0.80	-0.83	0.05	-0.75	0.80	-0.82	-0.04	-0.81	0.78	0.72	0.53		
Both Areas Minus 5 Sites in East Central Alberta and Innisfail Sites																	
Alfalfa (-N) 1st Cut	20	-0.78	-0.09	-0.77	0.52	-0.60	-0.15	-0.64	0.53	-0.47	-0.18	-0.52	0.54	0.81	0.78		
Alfalfa (-N) 2 Cuts	19	-0.78	-0.08	-0.78	0.55	-0.62	-0.14	-0.66	0.55	-0.48	-0.15	-0.54	0.56	0.82	0.80		
Alfalfa (+N) 1st Cut	20	-0.66	0.14	-0.56	0.65	-0.72	0.02	-0.66	0.64	-0.69	-0.08	-0.68	0.64	0.62	0.46		
Alfalfa (+N) 2 Cuts	18	-0.70	0.17	-0.64	0.64	-0.70	0.06	-0.67	0.64	-0.66	-0.02	-0.66	0.64	0.67	0.55		
Clover (-N)	18	-0.81	0.10	-0.68	0.84	-0.93	0.06	-0.87	0.84	-0.90	-0.17	-0.89	0.83	0.73	0.37		
Clover (+N)	18	-0.66	0.27	-0.52	0.86	-0.88	0.11	-0.80	0.85	-0.91	0.002	-0.89	0.83	0.59	0.20		
Olli Barley	15	-0.78	0.28	-0.70	0.86	-0.89	0.13	-0.83	0.84	-0.90	0.02	-0.89	0.83	0.73	0.45		
Galt Barley	15	-0.88	0.28	-0.81	0.92	-0.97	0.11	-0.95	0.92	-0.93	-0.02	-0.95	0.92	0.79	0.54		
Span Rape (Seed)	18	-0.37	0.18	-0.23	0.52	-0.52	0.09	-0.44	0.50	-0.58	0.008	-0.55	0.48	0.41	0.23		
Span Rape (Straw)	18	-0.74	0.43	-0.59	0.88	-0.88	0.33	-0.86	0.87	-0.89	0.24	-0.90	0.86	0.76	0.56		
Peace River Area																	
Alfalfa (-N) 1st Cut	13	-0.77	-0.20	-0.73	0.54	-0.60	-0.22	-0.62	0.55	-0.50	-0.20	-0.53	0.56	0.75	0.77		
Alfalfa (-N) 2 Cuts	12	-0.77	-0.16	-0.75	0.58	-0.63	-0.19	-0.66	0.59	-0.53	-0.18	-0.57	0.60	0.76	0.76		
Alfalfa (+N) 1st Cut	13	-0.66	0.11	-0.57	0.65	-0.71	-0.01	-0.66	0.64	-0.69	-0.08	-0.68	0.63	0.66	0.47		
Alfalfa (+N) 2 Cuts	12	-0.66	0.13	-0.59	0.65	-0.70	0.041	-0.65	0.65	-0.67	-0.01	-0.67	0.64	0.65	0.49		
Clover (-N)	13	-0.90	0.04	-0.74	0.86	-0.96	-0.11	-0.89	0.85	-0.93	-0.20	-0.92	0.84	0.84	0.39		
Clover (+N)	13	-0.73	0.28	-0.58	0.88	-0.92	0.11	-0.83	0.87	-0.94	0.002	-0.92	0.85	0.68	0.23		
Olli Barley	10	-0.76	0.39	-0.65	0.93	-0.96	0.23	-0.87	0.91	-0.98	0.11	-0.96	0.89	0.67	0.24		
Galt Barley	10	-0.87	0.29	-0.80	0.93	-0.98	0.13	-0.95	0.92	-0.95	0.02	-0.96	0.92	0.76	0.40		
Span Rape (Seed)	12	-0.49	0.57	-0.37	0.64	-0.64	0.54	-0.56	0.62	-0.68	0.51	-0.66	0.60	0.43	0.20		
Span Rape (Straw)	12	-0.80	0.65	-0.77	0.91	-0.92	0.59	-0.91	0.91	-0.91	0.53	-0.93	0.90	0.78	0.59		
1 Soluble Al and Soluble Mn -- extracted with 0.02 M CaCl ₂ . 2 Exchangeable Al -- extracted with 1 N KCl.																	

1 Soluble Al and Soluble Mn -- extracted with 0.02 M CaCl₂.

2 Exchangeable Al -- extracted with 1 N KCl.

APPENDIX VI

Correlation Coefficients for the Soil Criteria

	Correlation Coefficient (r)				
	Soluble Al	Exchangeable Al	% Base Saturation	pH in H ₂ O	pH in KCl
Soluble Al	---				
Exchangeable Al	0.98**	---			
% Base Saturation	-0.92**	-0.97**	---		
pH in Water	-0.57**	-0.61**	0.60**	---	
pH in KCl	-0.41*	-0.50*	0.57**	0.88**	---
Soluble Mn	-0.11	-0.10	0.14	-0.57**	-0.38

** and * indicate significance at the 1% and 5% levels, respectively.

APPENDIX VII

Percent Yields Used in Correlation and Regression Analyses

Area and Site	% Yield (No Lime x 100/Lime) by Crop and Treatment									
	Alfalfa (-N)		Alfalfa (+N)		Clover (-N)		Clover (+N)		Barley	
	1st Cut %	2 Cuts %	1st Cut %	2 Cuts %	(-N) %	(+N) %	(-N) %	(+N) %	Olli %	Galt %
<u>Central Alberta</u>										
Raessler	64	64	75	70	73	101	92	82	87	88
Bertsch	86	71	93	89	96	114	95	93	92	97
Hepp	56	53	97	91	--	--	93	86	81	75
Lyster	70	--	--	--	--	--	93	77	--	--
Kay	70	68	84	77	--	--	91	91	74	82
Innisfail North	--	--	--	--	--	--	103	98	95	92
Innisfail South	0	0	0	0	0	0	0	0	0	0
Cormie	32	33	89	77	92	90	91	82	90	88
Horen	51	39	85	76	130	125	--	--	--	--
Lowie	90	87	77	79	--	--	--	--	--	--
Weist	40	41	74	59	99	102	87	88	85	92
Webster	73	74	70	68	107	97	86	91	91	93
Cooking Lake	103	106	103	104	--	--	111	107	108	106
Williams	68	--	78	--	96	93	104	97	99	100

Appendix VII. (Continued)

Area and Site	% Yield (No Lime x 100/Lime) by Crop and Treatment									
	Alfalfa (-N)		Alfalfa (+N)		Clover (-N)		Clover (+N)		Barley	
	1st Cut %	2 Cuts %	1st Cut %	2 Cuts %	(-N) %	(+N) %	(-N) %	(+N) %	Olli %	Galt %
<u>Peace River</u>										
Valleyview North	41	38	82	77	108	112	97	86	108	89
Valleyview South	32	--	97	--	94	124	90	78	112	96
Derksen	15	19	48	45	87	88	92	91	--	--
Dyck	31	35	56	57	58	82	80	62	--	--
Wanham	14	24	50	43	98	106	--	--	123	107
Spirit River	52	69	75	76	106	109	92	94	103	101
Silver Valley	0	0	0	0	0	0	44	8	66	40
Fourth Creek	--	--	--	--	--	--	--	--	109	82
Wembley	95	92	93	81	119	94	95	92	106	97
Border	58	50	113	91	110	113	101	85	79	89
Bessborough	53	53	75	68	93	95	94	92	97	114
Prespatou	5	3	52	37	71	80	89	57	93	91
Hastings	75	88	94	101	97	97	--	--	96	106
Buick Creek	30	31	32	27	105	113	--	--	98	93

APPENDIX VIII

Correlation and Regression of Percent Yield with
Soil Al, Mn, pH, and Percentage Base Saturation

No. Sites	Crop	Simple Correlation Coefficient (r)		Standard Partial Regression Coefficient		Multiple Correlation Coefficient
<u>Both Areas Minus Innisfail South</u>						
		<u>Sol. Al</u>	<u>Sol. Mn</u>	<u>Sol. Al</u>	<u>Sol. Mn</u>	<u>(R)</u>
(22)	Alfalfa (-N)	-0.72** ³	-0.06	-0.78**	0.18	0.74**
(24)	Alfalfa (+N)	-0.70** ²	-0.002	-0.71**	0.06	0.70**
(20)	Clover (-N)	-0.92** ²	-0.22	-0.91**	-0.14	0.93**
(20)	Clover (+N)	-0.91** ¹	0.03	-0.91**	-0.06	0.91**
(21)	Olli Barley	-0.90** ²	-0.03	-0.90**	-0.01	0.90**
(21)	Galt Barley	-0.96** ²	-0.01	-0.96**	-0.01	0.96**
(22)	Span Rape					
	(Seed)	-0.47* ¹	-0.28	-0.59**	-0.44*	0.63**
(22)	Span Rape					
	(Straw)	-0.82** ¹	-0.04	-0.89**	-0.29*	0.86**
		<u>% Base Sat.</u>	<u>Sol. Mn</u>	<u>% Base Sat.</u>	<u>Sol. Mn</u>	<u>(R)</u>
(22)	Alfalfa (-N)	0.56**	-0.06	0.58**	-0.15	0.58**
(24)	Alfalfa (+N)	0.62**	-0.002	0.63**	-0.09	0.63**
(20)	Clover (-N)	0.82**	-0.22	0.87**	-0.35**	0.89**
(20)	Clover (+N)	0.82**	0.03	0.84**	-0.09	0.83**
(21)	Olli Barley	0.81**	-0.03	0.86**	-0.21	0.84**
(21)	Galt Barley	0.91**	-0.01	0.96**	-0.22*	0.93**
(22)	Span Rape					
	(Seed)	0.36	-0.28	0.44*	-0.37	0.51
(22)	Span Rape					
	(Straw)	0.78**	-0.04	0.83**	-0.21	0.81**
		<u>pH (H₂O)</u>	<u>Sol. Mn</u>	<u>pH (H₂O)</u>	<u>Sol. Mn</u>	<u>(R)</u>
(22)	Alfalfa (-N)	0.73**	-0.06	0.97**	0.46**	0.82**
(24)	Alfalfa (+N)	0.53**	-0.002	0.76*	0.41	0.63**
(20)	Clover (-N)	0.73**	-0.22	0.90**	0.30	0.77**
(20)	Clover (+N)	0.54*	0.03	0.84**	0.51*	0.69*
(21)	Olli Barley	0.71**	-0.03	0.98**	0.50**	0.83**
(21)	Galt Barley	0.73**	-0.01	1.03**	0.54**	0.86**
(22)	Span Rape					
	(Seed)	0.45*	-0.28	0.40	-0.16	0.48
(22)	Span Rape					
	(Straw)	0.72**	-0.04	0.77**	0.18	0.74**

Appendix VIII. (Continued)

No. Sites	Crop	Simple Correlation Coefficient (r)		Standard Partial Regression Coefficient		Multiple Correlation Coefficient
<u>Sites in the Peace River Region</u>						
		<u>Sol. Al</u>	<u>Sol. Mn</u>	<u>Sol. Al</u>	<u>Sol. Mn</u>	<u>(R)</u>
(12)	Alfalfa (-N)	-0.77** ³	-0.18	-0.80**	0.07	0.78**
(13)	Alfalfa (+N)	0.71** ²	-0.08	-0.71**	-0.01	0.71*
(13)	Clover (-N)	-0.96** ²	-0.20	-0.95**	-0.11	0.97**
(13)	Clover (+N)	-0.94** ¹	0.002	-0.95**	-0.07	0.94**
(10)	Olli Barley	-0.96** ²	0.006	-0.96**	0.03	0.96**
(10)	Galt Barley	-0.98** ²	0.02	-0.98**	0.05	0.98**
(12)	Span Rape					
	(Seed)	-0.68* ¹	0.51	-0.57	0.20	0.70
(12)	Span Rape					
	(Straw)	-0.91** ¹	0.53	-0.88**	0.06	0.92**
		<u>% Base Sat.</u>	<u>Sol. Mn</u>	<u>% Base Sat.</u>	<u>Sol. Mn</u>	<u>(R)</u>
(12)	Alfalfa (-N)	0.60*	-0.18	0.66*	-0.30	0.67
(13)	Alfalfa (+N)	0.63*	-0.08	0.66*	-0.20	0.66
(13)	Clover (-N)	0.84**	-0.20	0.91**	-0.36*	0.92**
(13)	Clover (+N)	0.85**	0.002	0.88**	-0.16	0.86**
(10)	Olli Barley	0.87**	0.006	0.93**	-0.25	0.90**
(10)	Galt Barley	0.92**	0.02	0.99**	-0.25	0.95**
(12)	Span Rape					
	(Seed)	0.60*	0.51	0.48	0.35	0.68
(12)	Span Rape					
	(Straw)	0.90**	0.53	0.82**	0.26	0.93**
		<u>pH (H₂O)</u>	<u>Sol. Mn</u>	<u>pH (H₂O)</u>	<u>Sol. Mn</u>	<u>(R)</u>
(12)	Alfalfa (-N)	0.76**	-0.18	0.96**	0.36	0.82**
(13)	Alfalfa (+N)	0.66*	-0.08	0.90*	0.42	0.75*
(13)	Clover (-N)	0.84**	-0.20	1.06**	0.38*	0.90**
(13)	Clover (+N)	0.68*	0.002	0.99**	0.55*	0.82**
(10)	Olli Barley	0.72*	0.006	1.00**	0.53*	0.85*
(10)	Galt Barley	0.76**	0.02	1.07*	0.58*	0.91**
(12)	Span Rape					
	(Seed)	0.43	0.51	0.45	0.35	0.62
(12)	Span Rape					
	(Straw)	0.78**	0.53	0.71**	0.41*	0.88**

Appendix VIII. (Continued)

No. Sites	Crop	Simple Correlation Coefficient (r)		Standard Partial Regression Coefficient		Multiple Correlation Coefficient
<u>Both Areas Minus 5 Sites in the South and the Innisfail Sites</u>						
		<u>Sol. Al</u>	<u>Sol. Mn</u>	<u>Sol. Al</u>	<u>Sol. Mn</u>	<u>(R)</u>
(18)	Alfalfa (-N)	-0.78** ³	-0.15	-0.79**	0.07	0.78**
(20)	Alfalfa (+N)	-0.72** ²	-0.08	-0.72**	-0.01	0.72**
(18)	Clover (-N)	-0.93** ²	-0.17	-0.92**	-0.10	0.93**
(18)	Clover (+N)	-0.91** ¹	-0.002	-0.92**	-0.08	0.92**
		<u>% Base Sat.</u>	<u>Sol. Mn</u>	<u>% Base Sat.</u>	<u>Sol. Mn</u>	<u>(R)</u>
(18)	Alfalfa (-N)	0.56*	-0.15	0.61**	-0.26	0.62*
(20)	Alfalfa (+N)	0.64**	-0.08	0.67**	-0.19	0.66**
(18)	Clover (-N)	0.83**	-0.17	0.89**	-0.33	0.89**
(18)	Clover (+N)	0.83**	-0.002	0.86**	-0.16	0.84**
		<u>pH (H₂O)</u>	<u>Sol. Mn</u>	<u>pH (H₂O)</u>	<u>Sol. Mn</u>	<u>(R)</u>
(18)	Alfalfa (-N)	0.82**	-0.15	0.98**	0.32*	0.87**
(20)	Alfalfa (+N)	0.62**	-0.08	0.77**	0.30	0.67**
(18)	Clover (-N)	0.73**	-0.17	0.89**	0.30	0.77**
(18)	Clover (+N)	0.59**	-0.002	0.83**	0.40	0.70**

* and ** indicates significance at the 5% and 1% levels, respectively.

¹ 0.02 M CaCl₂-Sol. Al.

² Square root 0.02 M CaCl₂-Sol. Al.

³ Log 0.02 M CaCl₂-Sol. Al.

APPENDIX IX

Nodulation Assessment of Alfalfa and Clover Grown on Limed and Unlimed Soil at 24 Sites

Site	Crop and Treatment	Color		Number ¹		Size ²		Position		Total Score
		% Pink	Score	N,S, or F	Score	S,M, or L	Score	Crown		
								%	Score	
Central Alberta										
Raessler	C + L + N	30	1	S	3	S	0	40	1	5
	C + L - N	80	3	S	3	S	0	60	2	8
	C - L + N	30	1	S	3	S	0	40	1	5
	C - L - N	50	2	S	3	S	0	50	1	6
	A + L + N	20	0	F	1	S	0	30	1	2
	A + L - N	90	4	S	3	S-M	1	30	1	9
	A - L + N	0	0	V F	0	S	0	0	0	0
	A - L - N	0	0	F	1	M	1	0	0	2
	C + L + N	20	0	N	2	S	0	30	1	3
	C + L - N	70	3	N	2	S-M	1	30	1	7
	C - L + N	70	3	N	2	S	0	30	1	6
	C - L - N	60	2	N	2	S-M	1	30	1	6
Bertsch	A + L + N	20	0	F	1	S	0	10	0	1
	A + L - N	90	3	S	3	S-M	1	70	1	8
	A - L + N	0	0	O	0	O	0	0	0	0
	A - L - N	0	0	F	1	S	0	0	0	1
	C + L + N	25	0	S	3	S	0	30	1	4
	C + L - N	80	3	N	2	S-M	1	50	2	8
	C - L + N	25	0	S	3	S	0	30	1	4
	C - L - N	60	2	N	2	S-M	1	50	2	7
Hepp	A + L + N	20	0	S	3	S	0	20	1	4
	A + L - N	80	3	N	2	S-M	1	30	1	7
	A - L + N	0	0	F	1	S	0	5	0	1
	A - L - N	15	0	S	3	S-M	1	0	0	4

Appendix IX. (Continued)

Site	Crop and Treatment	Number ¹		Size ²		Position		Total Score
		N, S, or F	Score	S, M, or L	Score	% Crown	Score	
			Color % Pink					
Lyster	A + L + N	F	0	S	0	60	2	3
	A + L - N	F	50	S	0	60	2	5
	A - L + N	V F	0	S	0	0	0	0
	A - L - N	F	60	S	0	60	2	5
Kay	C + L + N	S	50	S	0	10	0	5
	C + L - N	N	80	S-M	1	10	0	6
	C - L + N	S	50	S	0	10	0	5
	C - L - N	N	80	S-M	1	10	0	6
	A + L + N	F	50	S-M	1	20	1	5
	A + L - N	S	50	S-M	1	20	1	7
	A - L + N	V F	10	S	0	0	0	0
	A - L - N	F	10	S	0	30	1	2
Cormie	C + L + N	N	50	S	0	30	1	5
	C + L - N	N	70	S-M	1	30	1	7
	C - L + N	N	50	S	0	30	1	5
	C - L - N	N	50	S	0	30	1	5
	A + L + N	S	50	S-M	1	40	1	7
	A + L - N	S	70	S-M	1	50	1	8
	A - L + N	F	0	S	0	0	0	1
	A - L - N	F	15	S	0	50	1	2
Horen	C + L + N	N	30	S	0	10	0	3
	C + L - N	N	90	S-M	1	20	1	8
	C - L + N	N	10	S	0	10	0	2
	C - L - N	N	60	S-M	1	20	1	6
	A + L + N	S	20	S-M	1	70	2	6
	A + L - N	S	60	S-M	1	70	2	8
	A - L + N	S	0	S-M	1	70	2	6
	A - L - N	S	0	S-M	1	70	2	6

Appendix IX. (Continued)

Site	Crop and Treatment	Color		Number 1		Size 2		Position		Total Score
		% Pink	Score	N, S, or F	Score	S, M, or L	Score	% Crown	Score	
Weist	C + L + N	20	0	N	2	S	0	20	1	3
	C + L - N	50	2	N	2	S	0	30	1	5
	C - L + N	20	0	N	2	S	0	20	1	3
	C - L - N	50	2	N	2	S	0	30	1	5
	A + L + N	0	0	S	3	S-M	1	20	1	5
	A + L - N	50	2	S	3	S-M	1	70	1	7
	A - L + N	0	0	F	1	S-M	1	20	1	3
	A - L - N	0	0	F	1	S-M	1	50	1	3
Lowie	A + L + N	30	1	N	2	S-M	1	50	1	5
	A + L - N	70	3	N	2	S-M	1	50	1	7
	A - L + N	20	0	N	2	S-M	1	50	1	4
	A - L - N	50	1	N	2	S-M	1	70	2	6
Webster	C + L + N	20	0	N	2	S	0	20	1	3
	C + L - N	70	3	N	2	S	0	20	1	6
	C - L + N	20	0	N	2	S	0	20	1	3
	C - L - N	50	2	N	2	S	0	20	1	5
	A + L + N	30	1	S	3	S-M	1	30	1	6
	A + L - N	80	3	S	3	S-M	1	50	1	8
	A - L + N	10	0	S	3	S-M	1	30	1	5
	A - L - N	0-30	1	F	1	S	0	60	2	4
Cooking Lake	A + L + N	0	0	S	3	S-M	1	20	1	5
	A + L - N	80	3	S	3	S-M	1	20	1	8
	A - L + N	0	0	S	3	S-M	1	20	1	5
	A - L - N	70	3	S	3	S-M	1	20	1	8

Appendix IX. (Continued)

Site	Crop and Treatment	Color		Number 1		Size 2		Position		Total Score
		% Pink	Score	N, S, or F	Score	S, M, or L	Score	% Crown	Score	
Williams	C + L + N	70	3	N	2	S	0	50	1	6
	C + L - N	70	3	N	2	S	0	50	1	6
	C - L + N	70	3	N	2	S	0	50	1	6
	C - L - N	70	3	N	2	S	0	50	1	6
	A + L + N	10	0	S	3	S-M	1	70	2	6
	A + L - N	80	3	5	3	S-M	1	70	2	9
	A - L + N	10	0	S	3	S-M	1	70	2	6
	A - L - N	60	2	S	3	S-M	1	70	2	8
<u>Peace River</u>										
Valleyview North	A + L + N	100	4	F	1	S-M	1	10	0	6
	A + L - N	100	4	S	3	M-S	1	20	1	9
	A - L + N	0	0	0	0	-	0	0	0	0
	A - L - N	0	0	0	0	-	0	0	0	0
Wanham	A + L + N	100	4	F	1	M	1	10	0	6
	A + L - N	100	4	S	3	M	1	50	1	9
	A - L + N	0	0	V V F	0	S	0	0	0	0
	A - L - N	0	0	F F	1	M	1	0	0	2
Spirit River	C + L + N	100	4	N	2	S	0	20	1	7
	C + L - N	100	4	N	2	S	0	30	1	7
	C - L + N	100	4	N	2	S	0	20	1	7
	C - L - N	100	4	N	2	S-M	1	30	1	8
	A + L + N	100	4	S-F	3	M	1	20	1	9
	A + L - N	100	4	S-F	3	M-L	1	80	2	10
	A - L + N	100	4	F-S	3	S-L	1	30	1	9
	A - L - N	100	4	F	1	L	0	70	2	7

Appendix IX. (Continued)

Site	Crop and Treatment	Number ¹		Size ²		Position		Total Score
		N,S, or F	Score	S,M, or L	Score	% Crown	Score	
Silver Valley	C + L + N	S	3	M	1	20	1	9
	C + L - N	S	3	M	1	5	0	8
	C - L + N	0	0	-	0	0	0	0
	C - L - N	0	0	-	0	0	0	0
	A + L + N	S	3	M	1	5	0	8
	A + L - N	S	3	M	1	10	0	8
	A - L + N	0	0	-	0	0	0	0
	A - L - N	0	0	-	0	0	0	0
La Crete, Dyck	C + L + N	F	1	S	0	25	1	6
	C + L - N	S	3	M	1	15	0	8
	C - L + N	F	1	S-M	1	50	1	6
	C - L - N	F	1	M-L	1	50	1	7
	A + L + N	S	3	S	0	10	0	7
	A + L - N	S	3	S-M	1	10	0	8
	A - L + N	F	1	M-L	1	50	1	5
	A - L - N	F	1	L	0	0	0	1
	C + L + N	S	3	S	0	10	0	7
	C + L - N	S	3	M	1	20	1	9
	C - L + N	S	3	M	1	20	1	9
	C - L - N	S	3	M	1	20	1	9
La Crete, Derksen	A + L + N	F	1	S	0	20	1	6
	A + L - N	S	3	S-M	1	10	0	8
	A - L + N	F	1	M-L	1	60	2	6
	A - L - N	F	1	L	0	0	0	1
	C + L + N	S	3	S	0	10	0	7
	C + L - N	S	3	M	1	20	1	9
	C - L + N	S	3	M	1	20	1	9
	C - L - N	S	3	M	1	20	1	9

Appendix IX. (Continued)

Site	Crop and Treatment	Color		Number ¹		Size ²		Position		Total Score
		% Pink	Score	N, S, or F	Score	S, M, or L	Score	% Crown	Score	
Wembley	A + L + N	100	4	F	1	S	0	5	0	5
	A + L - N	90	4	S	2	M	1	5	0	7
	A - L + N	75	3	F	1	S	0	0	0	4
	A - L - N	90	4	F	1	S-M	1	0	0	6
Border	C + L + N	100	4	N	2	S	0	20	1	7
	C + L - N	100	4	N	2	S	0	20	1	7
	C - L + N	100	4	N-S	2	S	0	20	1	7
	C - L - N	100	4	N	2	S	0	10	0	6
	A + L + N	100	4	N	2	M	1	20	1	8
	A + L - N	100	4	S	3	M-L	1	10	0	8
	A - L + N	0	0	F	1	S	0	0	0	1
	A - L - N	50	2	F	1	M	1	0	0	4
Bessborough	C + L + N	90	4	S	3	S	0	10	0	7
	C + L - N	100	4	N	2	S	0	5	0	6
	C - L + N	100	4	S	3	S	0	5	0	7
	C - L - N	100	4	N	2	S	0	10	0	6
	A + L + N	100	4	S	3	S-M	1	10	0	8
	A + L - N	100	4	N	2	M-L	1	10	0	7
	A - L + N	100	4	F	1	M	1	10	0	6
	A - L - N	100	4	S	3	M-L	1	50	1	9
Hastings No. 1	C + L + N	100	4	S	3	S	0	20	1	8
	C + L - N	90	4	S-N	3	S	0	5	0	7
	C - L + N	100	4	S	3	S	0	5	0	7
	C - L - N	100	4	S	3	S	0	20	1	8

Appendix IX. (Continued)

Site	Crop and Treatment	Color		Number ¹		Size ²		Position		Total Score
		% Pink	Score	N, S, or F	Score	S, M, or L	Score	% Crown	Score	
Hastings No. 2 (Buick Creek)	A + L + N	100	4	S	3	S	0	2	0	7
	A + L - N	100	4	F-S	3	S-M	1	5	0	8
	A - L + N	100	4	F-S	3	M	1	20	1	9
	A - L - N	100	4	S	3	M-L	1	2	0	8
	C + L + N	100	4	N	2	S	0	10	0	6
	C + L - N	100	4	N	2	S	0	10	0	6
	C - L + N	100	4	N	2	S-M	1	10	0	7
	C - L - N	100	4	N	2	S	0	5	0	6
	A + L + N	100	4	S-N	3	S-M	1	5	0	8
	A + L - N	100	4	N	2	S-M	1	10	0	7
	A - L + N	30	1	F	1	M	1	10	0	3
	A - L - N	50	3	S	3	M-L	1	40	1	8
Prespatou	C + L + N	100	4	N	2	S	0	5	0	6
	C + L - N	100	4	N	2	S	0	10	0	6
	C - L + N	90	4	S	3	S	0	5	0	7
	C - L - N	100	4	S-N	3	S-M	1	25	1	9
	A + L + N	100	4	S	3	S-M	1	10	0	8
	A + L - N	100	4	S	3	M	1	20	1	9
	A - L + N	20	0	F	1	S-M	1	0	0	2
	A - L - N	60	2	F	1	L	0	80	2	5

Crop and Treatment

C + L + N Clover: Lime plus Nitrogen A + L + N Alfalfa: Lime plus Nitrogen
C + L - N Clover: Lime, no Nitrogen A + L - N Alfalfa: Lime, no Nitrogen
C - L + N Clover: No Lime plus Nitrogen A - L + N Alfalfa: No Lime plus Nitrogen
C - L - N Clover: No Lime, no Nitrogen A - L - N Alfalfa: No Lime, no Nitrogen

¹ Number -- N, S and F indicate numerous, some, and few, respectively.

² Size -- S, M and L indicate small, medium, and large, respectively.

APPENDIX X

Statistical Significance of Lime, Varieties, Nitrogen and the Lime x Variety and Lime x Nitrogen Interaction from 28 Field Experiments

Site	Crop									
	Barley			Rape	Alfalfa			Red Clover		
	Lime	Varieties	LxV ¹	Lime	Lime	Nitrogen	LxN ²	Lime	Nitrogen	LxN ²
Raessler	*	N.S.	N.S.	N.S.	**	N.S.	N.S.	N.S.	N.S.	N.S.
Bertsch	N.S.	N.S.	N.S.	N.S.	N.S.	*	*	N.S.	N.S.	N.S.
Hepp	N.S.	N.S.	N.S.	N.S.	*	*	N.S.	--	--	--
Lyster	N.S.	N.S.	N.S.	N.S.	N.S.	*	N.S.	--	--	--
Kay	*	**	N.S.	*	**	N.S.	N.S.	--	--	--
Innisfail North	N.S.	*	N.S.	N.S.	N.S.	N.S.	N.S.	--	--	--
Innisfail South	**	*	N.S.	**	**	N.S.	N.S.	--	--	--
Cormie	N.S.	N.S.	N.S.	N.S.	**	**	**	N.S.	N.S.	N.S.
Horen	--	--	--	--	**	N.S.	N.S.	N.S.	N.S.	N.S.
Weist	N.S.	**	N.S.	N.S.	*	*	N.S.	N.S.	N.S.	N.S.
Webster	N.S.	**	N.S.	N.S.	*	N.S.	N.S.	N.S.	N.S.	N.S.
Lowie	--	--	--	--	N.S.	N.S.	N.S.	--	--	--
Cooking Lake	N.S.	*	--	N.S.	N.S.	N.S.	N.S.	*	N.S.	N.S.

Appendix X. (Continued)

Site	Crop									
	Barley			Rape	Alfalfa			Red Clover		
	Lime	Varieties	LxV ¹	Lime	Nitrogen	LxN ²	Lime	Nitrogen	LxN ²	
Williams	N.S.	**	--	N.S.	**	N.S.	N.S.	N.S.	N.S.	N.S.
Valleyview North	N.S.	N.S.	N.S.	N.S.	**	**	N.S.	N.S.	N.S.	N.S.
Valleyview South	*	N.S.	N.S.	N.S.	**	*	N.S.	N.S.	*	**
Derksen	N.S.	*	N.S.	N.S.	**	--	N.S.	N.S.	N.S.	N.S.
Dyck	N.S.	N.S.	N.S.	N.S.	**	*	N.S.	N.S.	N.S.	N.S.
Wanham	N.S.	*	N.S.	N.S.	**	*	N.S.	N.S.	N.S.	*
Spirit River	N.S.	N.S.	N.S.	N.S.	*	N.S.	N.S.	N.S.	N.S.	N.S.
Silver Valley	**	*	N.S.	N.S.	**	N.S.	N.S.	**	N.S.	N.S.
Fourth Creek	N.S.	N.S.	N.S.	N.S.	--	--	--	--	--	--
Wembley	*	**	N.S.	N.S.	*	N.S.	N.S.	N.S.	N.S.	N.S.
Border	*	N.S.	N.S.	N.S.	*	**	N.S.	N.S.	N.S.	N.S.
Bessborough	N.S.	N.S.	N.S.	N.S.	*	*	N.S.	N.S.	N.S.	N.S.
Prespatou	N.S.	*	*	N.S.	**	*	N.S.	N.S.	*	N.S.
Hastings	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Buick Creek	N.S.	N.S.	N.S.	N.S.	**	N.S.	N.S.	N.S.	N.S.	N.S.

* and ** indicates statistical significance at the 5% and 1% levels, respectively.

¹ L x V is the interaction of lime and variety. ² L x N is the interaction of lime and nitrogen.

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